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Enabling the Grid of the Future through Advanced Controls

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Sandia National Laboratories

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So what is the "Smart Grid" … ?

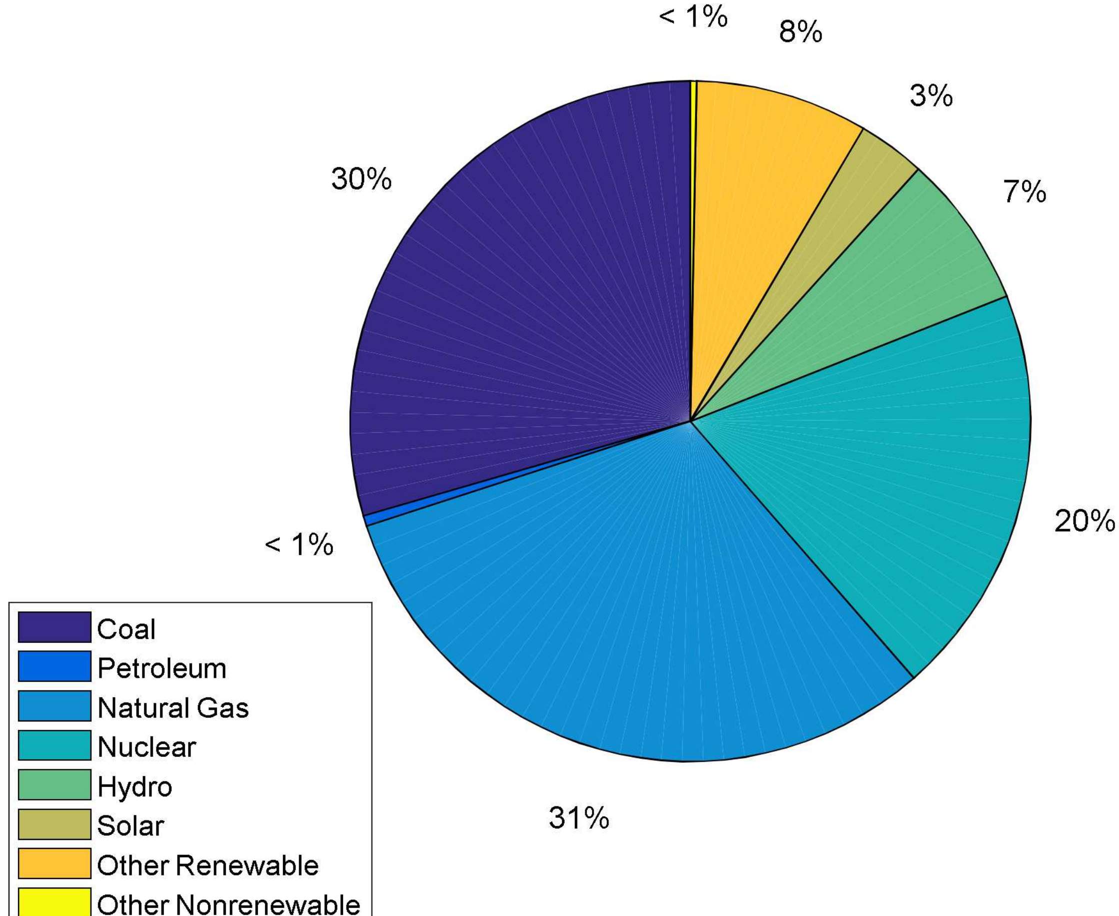
- The SMART Grid has several elements
  - Includes "Smart" energy resources
  - Uses Digital Communication to manage power generation, usage, transfer, and consumption
  - Improved situational awareness of grid operation through distributed sensing

- And several objectives
  - Increased Renewable Energy Integration
  - Improved Flexibility
  - Improved Efficiency, Reliability, and Resiliency

Attributes of Renewable and Non-Renewable Energy Sources

Electricity in the US is primarily from Non-renewable Sources

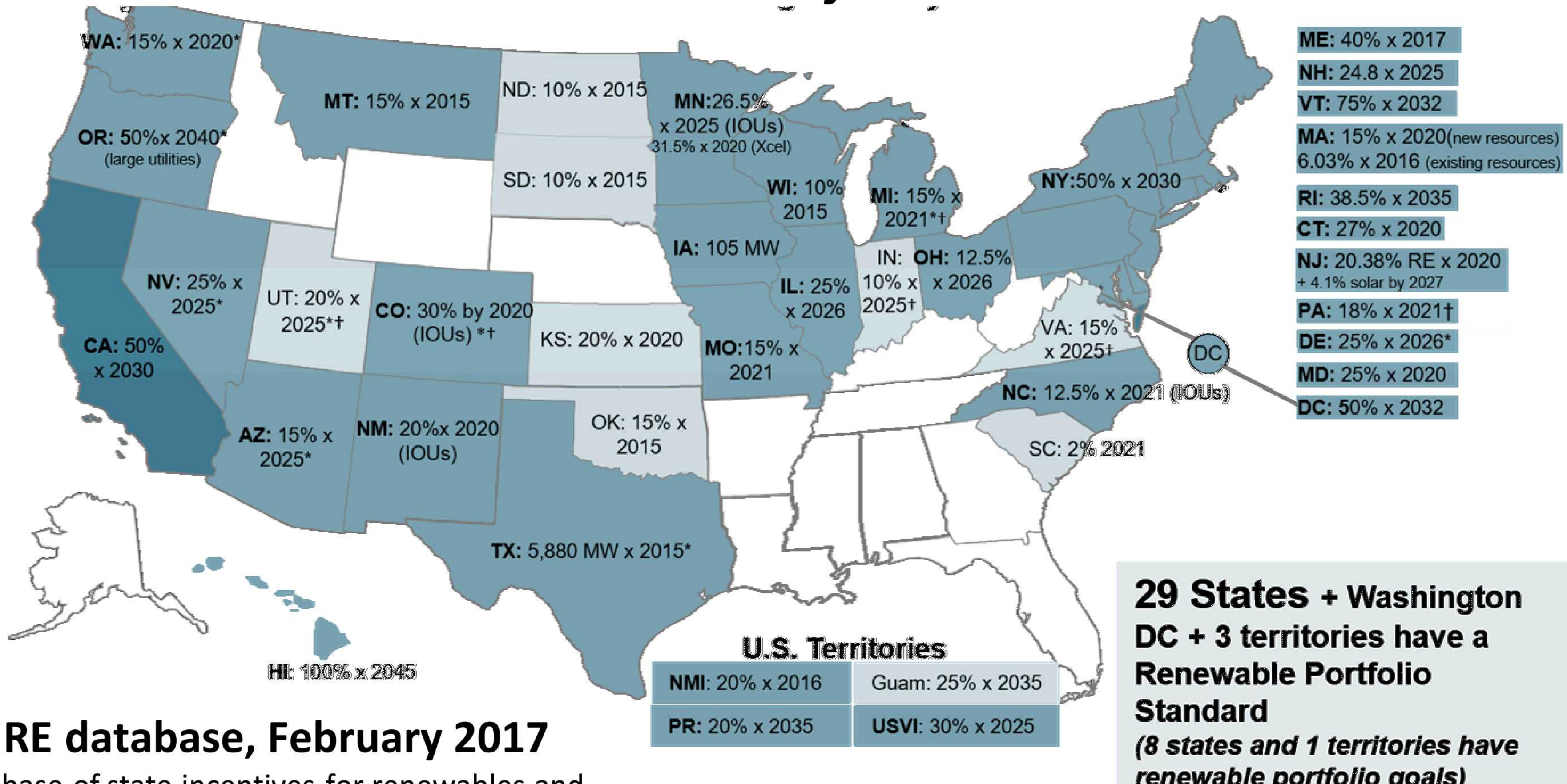
2017: 81.3% of US electric power from non-renewable sources



US Energy Information Administration: https://www.eia.gov/electricity/monthly/

States are Committing to Renewable Energy Integration

- **29 state governments, Washington DC, 3 territories have committed to new *Renewable Portfolio Standards***

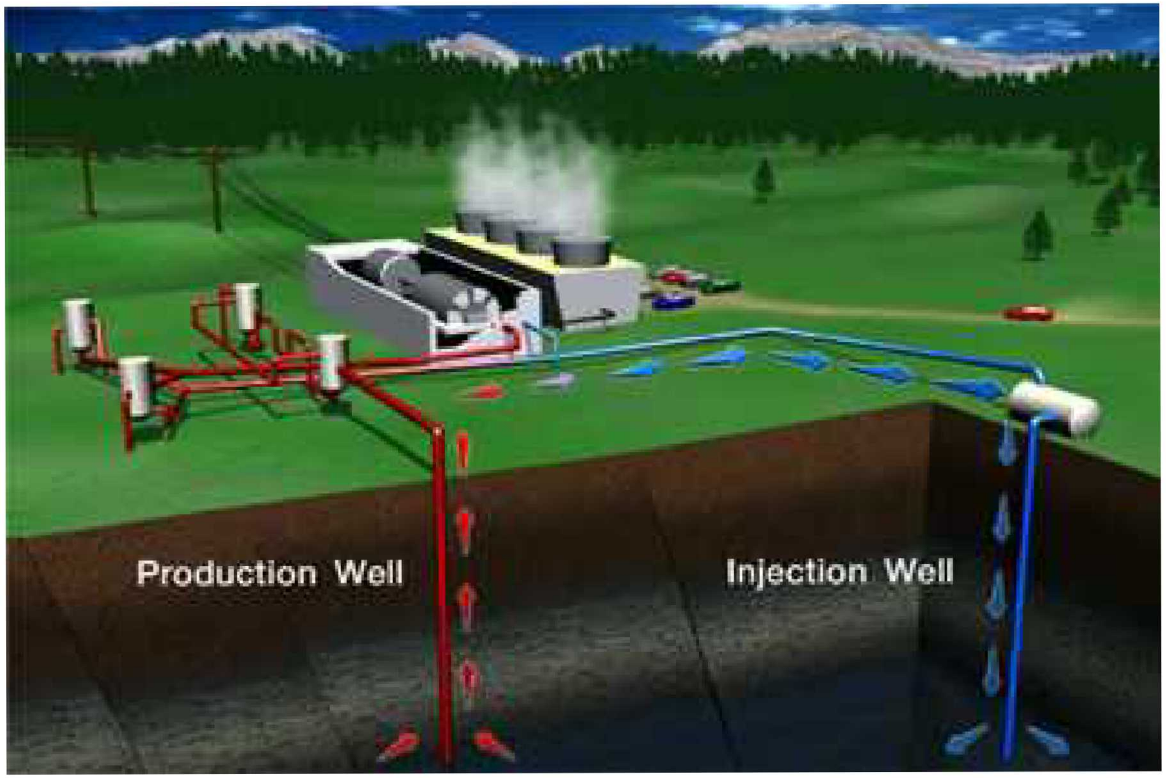


DSIRE database, February 2017

Database of state incentives for renewables and efficiency renewable portfolio standards
http://www.dsireusa.org/

Geo-Thermal Energy

- **Water is heated by thermal energy in the earth's crust, converted to steam and used to drive a steam turbine generator**

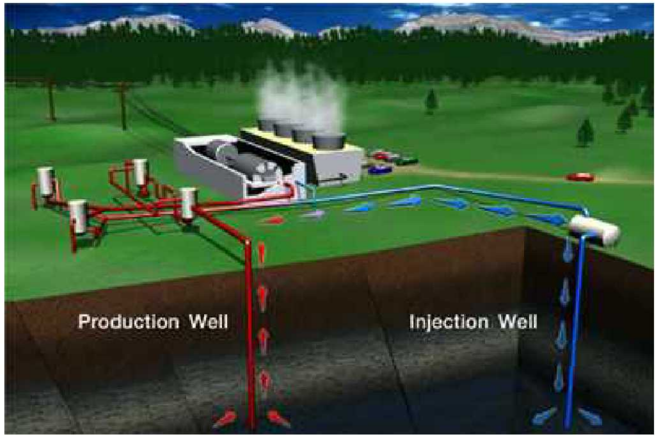


D. Chandler, "Power from Down Under", MIT News office, January 26, 2010
http://web.mit.edu/newsoffice/2010/geothermal-0126.html

Geo-Thermal Energy

In 2017, the US consumed an estimated 4.01 Trillion kilo-Watt-hours of electricity[1]

- **In 2013, US geothermal capacity was 11.4 GW[2], producing nearly 16.9 Billion kWh[3] (0.4%)**
- **Existing plants tend to be under-utilized[4]**
  - 73% utilization can be increased to 92%[2,4]
- **Lowest Land Use of all renewables[5]**



[1] https://www.eia.gov/
[2]http://en.wikipedia.org/wiki/Geothermal_energy_in_the_United_States
[3]British Petroleum: http://www.bp.com/en/global/corporate/about-bp/statistical-review-of-world-energy-2013/review-by-energy-type/renewable-energy/geothermal-capacity.html (retrieved 11/10/2013)
[4] L.X. Richter; "Capacity factors of geothermal plants, a global analysis by Bloomberg New Energy Finance" , January 2012, http://thinkgeoenergy.com/archives/9644
[5] Levitan,D; "Report Counts Up Solar Power Land Use Needs" IEEE Spectrum Magazine; August 7, 2013.

Hydroelectric Power

- **Power is extracted from the potential energy of water**

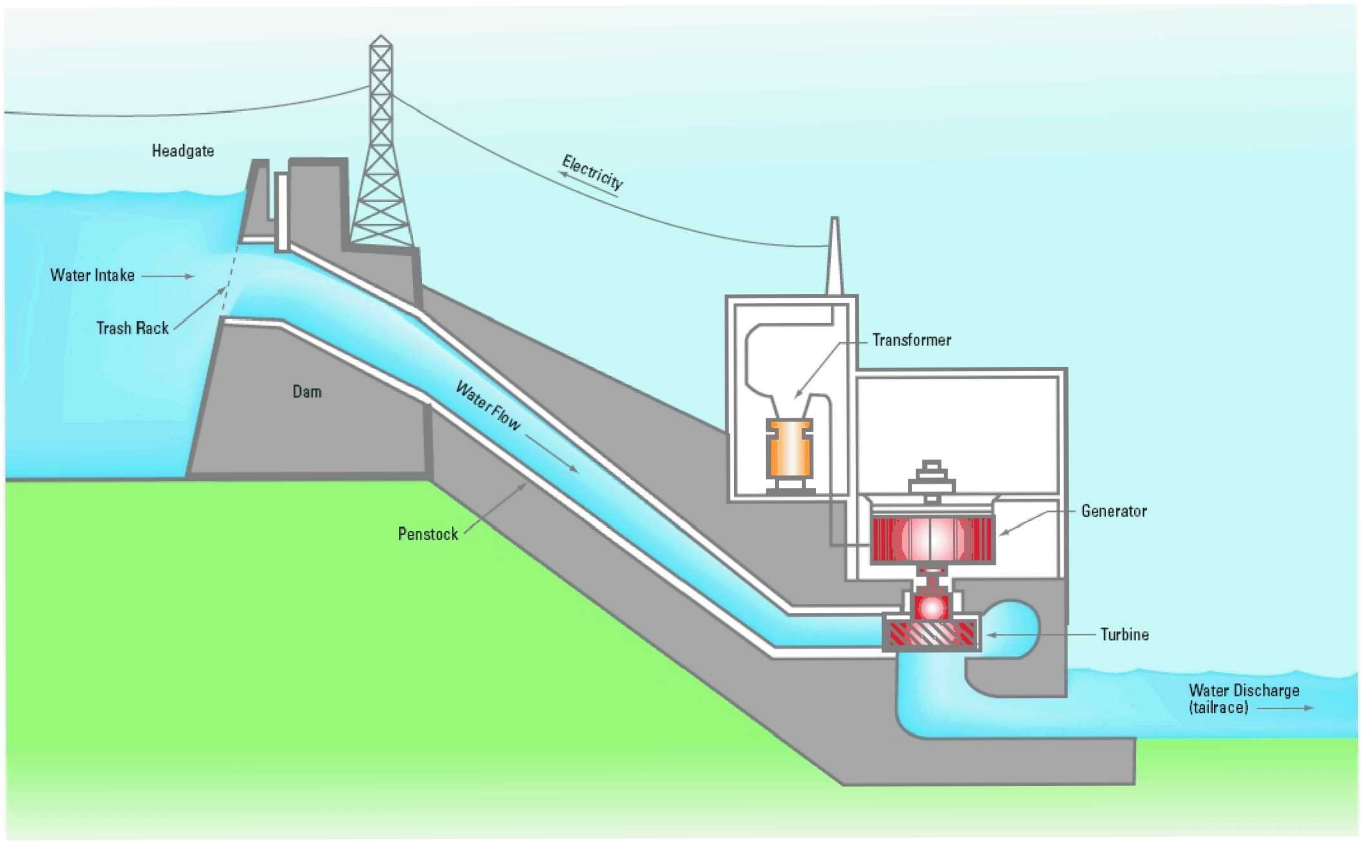
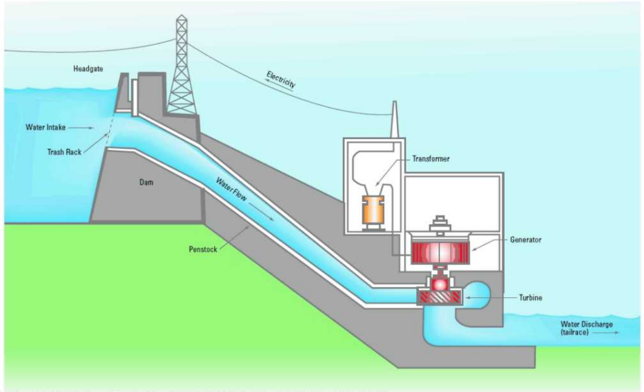


Illustration credit: Ontario Power Generation Inc.
http://www.opg.com/power/images/hydrohow.jpg

Hydroelectric Power

In 2017, the US consumed an estimated <u>4.01 Trillion</u> kilo-Watt-hours of electricity

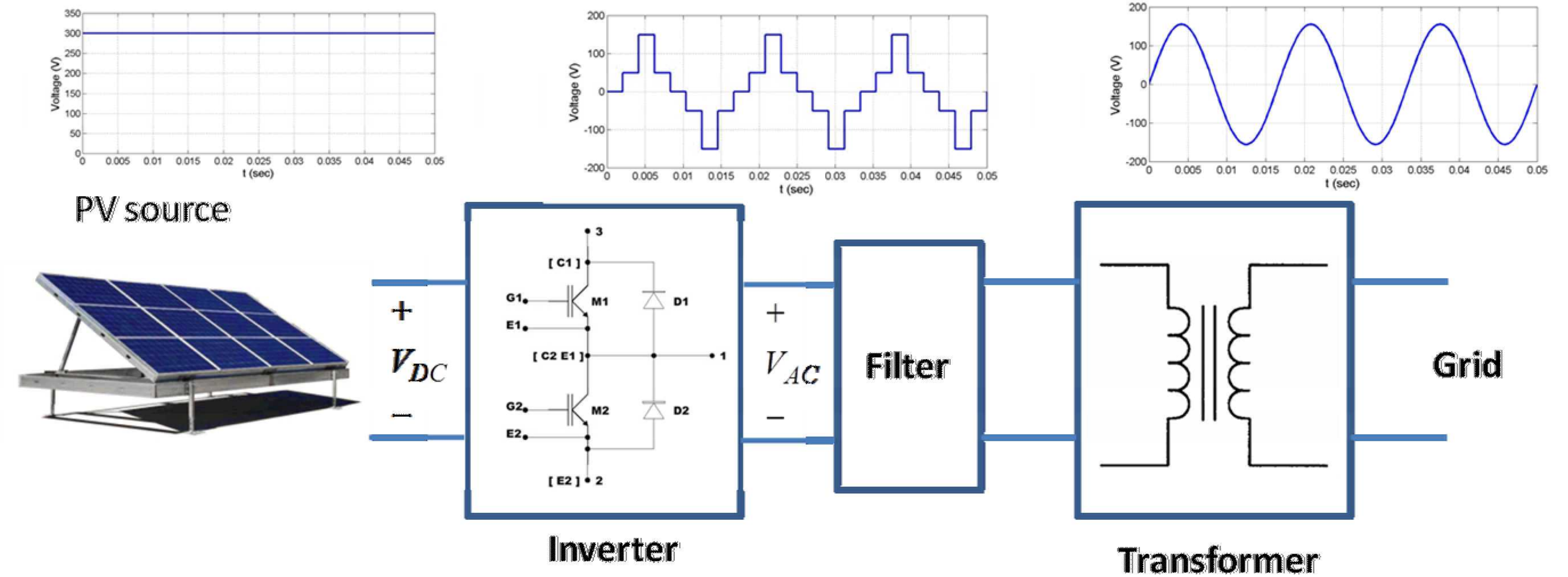
- **270-370 Billion kWh of Hydroelectric power produced annually (6.5-9.0%)[1,2]**
- **In 2013 was 75% of nation's total renewable electricity[2]; in 2017, approx. 40%**
- **Currently cheapest source of electricity: Average 1.5¢ / kWh[2]**
- **About 90% efficient[2]**
- **Adding generators to 600 dams could increase hydroelectricity by 15%[2]**



[1] S. McArthur and T. Brekken, "Ocean wave power data generation for grid integration studies," IEEE Power and Energy Society General Meeting, July 2010.
[2] US congressional committee on natural resources http://naturalresources.house.gov/issues/issue/?IssueID=8267

Photovoltaics

- Electrical Power is extracted directly from sunlight
- DC electrical power is converted to AC, filtered and injected to the grid



Photovoltaics

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In 2017, the US consumed an estimated <u>4.01 Trillion</u> kilo-Watt-hours of electricity

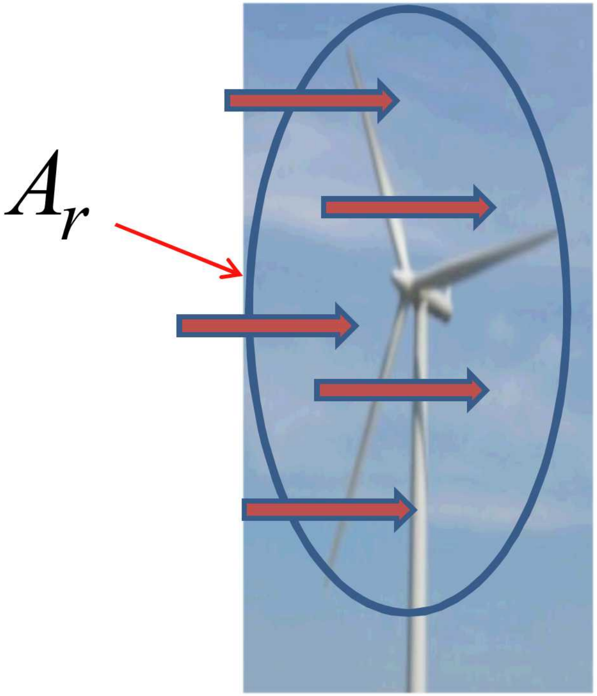
- **10,000[1]-23,000[2] square miles needed to meet US electricity needs (100%), approx 10-23% the land area of Nevada**
- **5,750 square miles needed to meet household demand[3]**

[1] "Renewable Energy - Modern Marvels." *Modern Marvels*. The History Channel. Season 13 episode 41. September 20, 2006. Television.
[2] Sean Ong, Clinton Campbell, Paul Denholm, Robert Margolis, and Garvin Heath; "Land-Use Requirements for Solar Power Plants in the United States"; NREL Technical Report; June 2013.
[3] Levitan,D; "Report Counts Up Solar Power Land Use Needs" IEEE Spectrum Magazine; August 7, 2013.

Wind Turbines

- Power is extracted from the kinetic Energy in the Wind
- Most new wind also connects to the grid using power electronics

$$P_{turb} = \frac{1}{2} C_p(\lambda) \rho_w A_r v_w^3$$



Wind Turbines

In 2017, the US consumed an estimated 4.01 Trillion kilo-Watt-hours of electricity

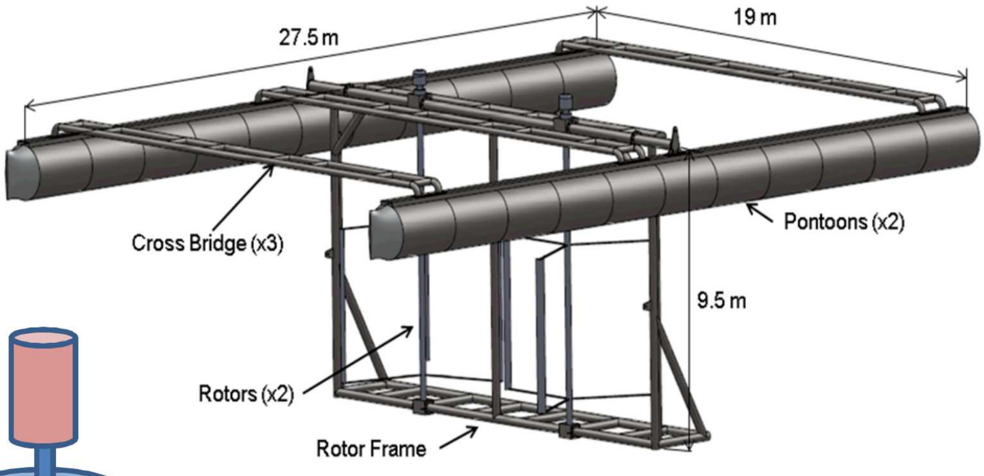
- **Between 121,000 – 202,000 square miles of Wind needed to meet US energy needs (100%)[1]**
- **There's enough wind in North and South Dakota (~147,000 square miles) to meet US energy needs[2]**

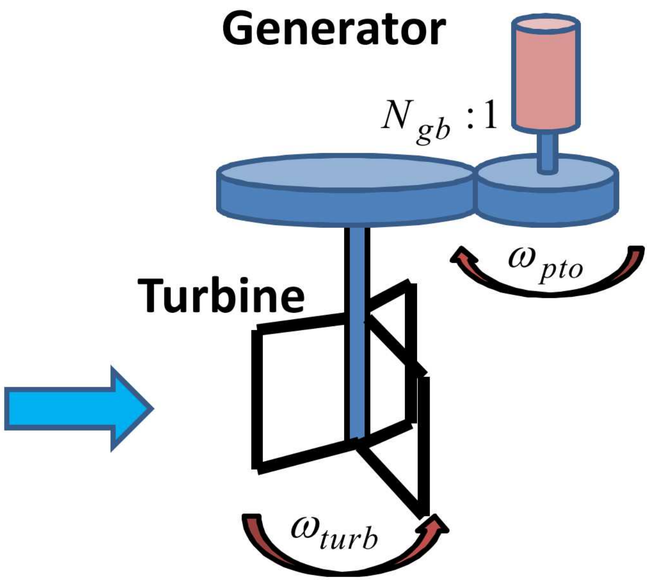
[1] Paul Denholm, Maureen Hand, Maddalena Jackson, and Sean Ong "Land-Use Requirements of Modern Wind Power Plants in the United States "NREL Technical Report; August 2009.
[2] "Renewable Energy - Modern Marvels." *Modern Marvels*. The History Channel. Season 13 episode 41. September 20, 2006. Television.

River Turbine

- **Power is extracted from the flow of water**
- **Connects to the grid through power electronics**

$$P_{turb} = \frac{1}{2} C_p(\lambda) \rho_w A_r v_w^3$$

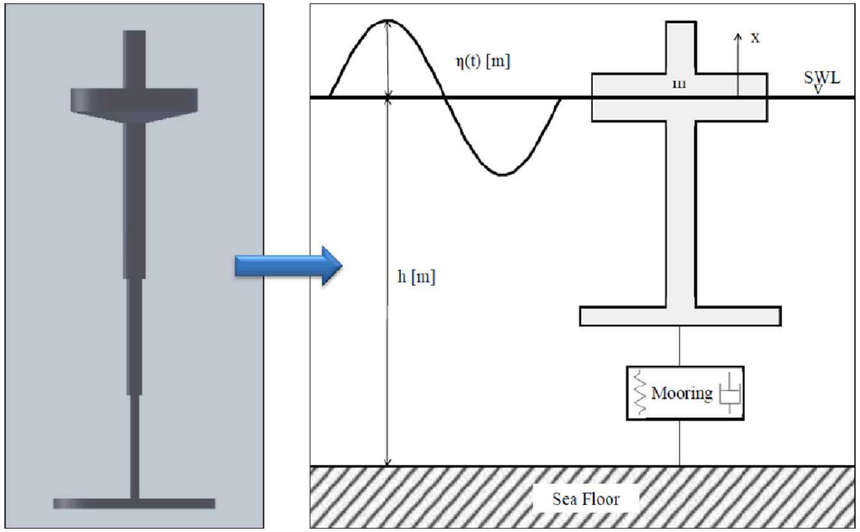


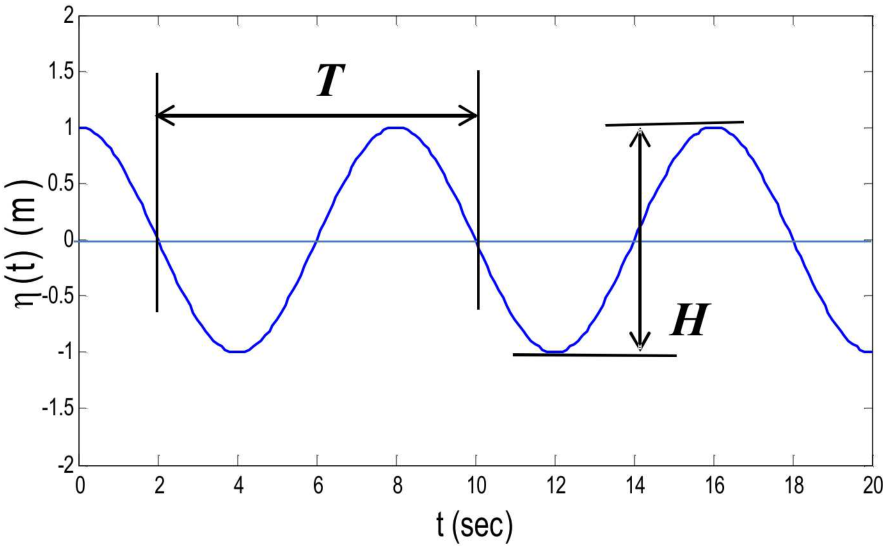


Wave Energy

- **Power is extracted from wave motion**
- **Connects to the grid through power electronics**

$$P_{wave} = \frac{\rho_{sw} g^2 H^2 T}{32\pi} CW$$





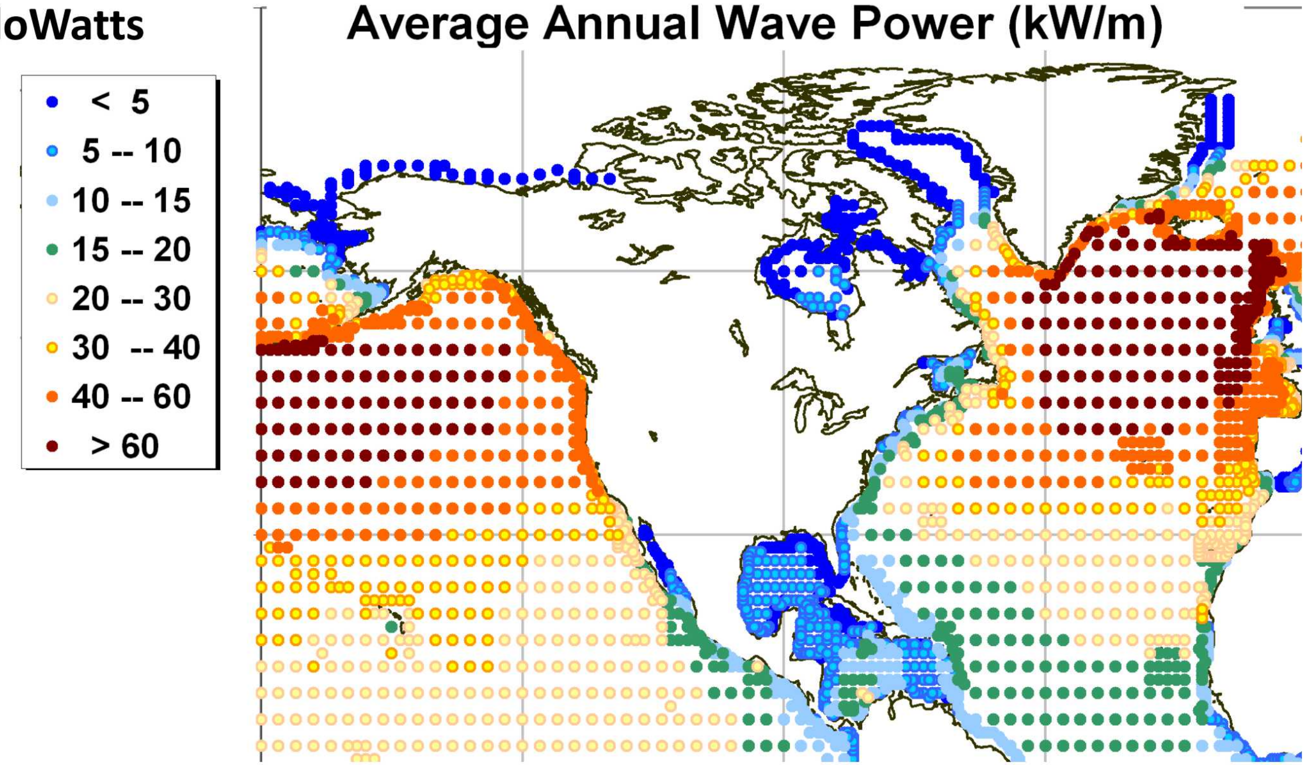
Wave Energy

Sandia National Laboratories

In 2017, the US consumed an estimated <u>4.01 Trillion</u> kilo-Watt-hours of electricity

- **440 Billion kWh of wave energy available on West coast[1] (~10.9%)**

Average KiloWatts Per meter[1]



[1] S. McArthur and T. Brekken, "Ocean wave power data generation for grid integration studies," IEEE Power and Energy Society General Meeting, July 2010.

Power versus Energy

- **Let's consider briefly a simple household use of power**

$$\text{Energy} = \text{Power} \times \text{Time}$$

100 W Light bulb

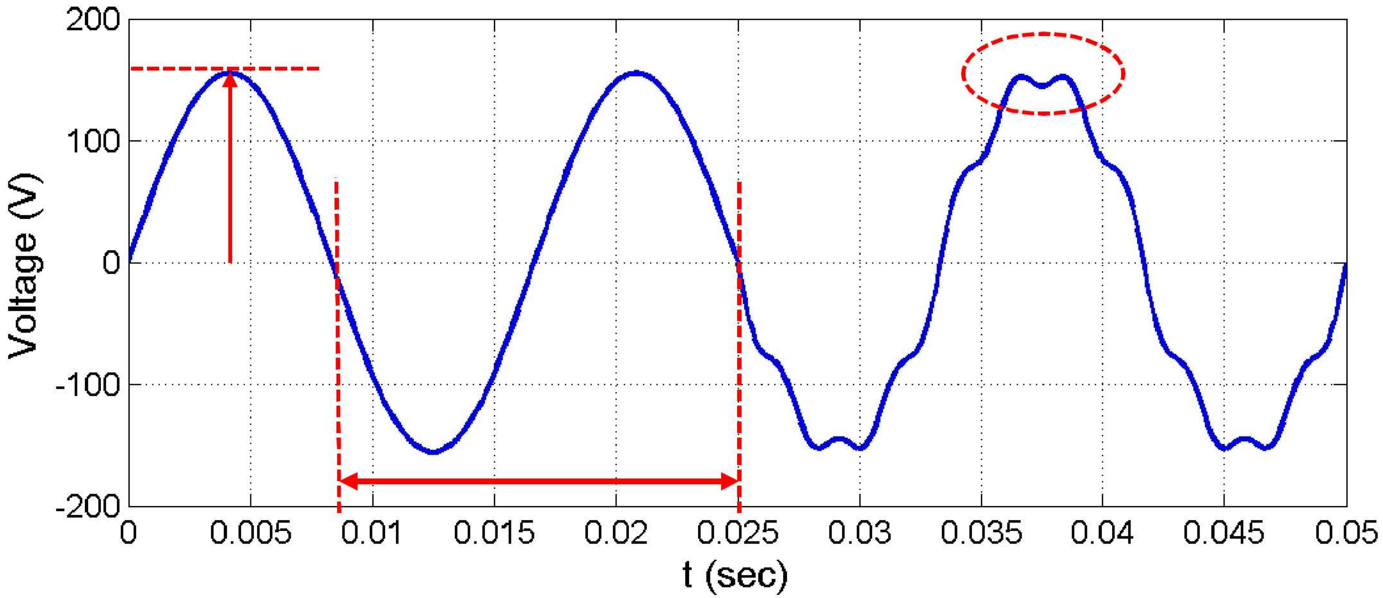
$$100\ \text{W} \times 2\ \text{hours}\ =\ 200\ \text{Watt} \cdot \text{hours}$$

100 W Light bulb

$$100\ \text{W} \times 10\ \text{hours}\ =\ 1\ \text{kiloWatt} \cdot \text{hour (kWh)}$$

Power Quality, Continuity of Service, Safety and Cost Matter

- Grid Frequency is regulated and limits are set
- Voltage Amplitude is controlled
- Harmonic content is limited
- Electricity is available almost all the time



Power Quality, Continuity of Service, Safety and Cost Matter

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- **System Average Interruption Duration Index (SAIDI)[1]**
- **Typically < 90-100 minutes per year**
- **Basically, Power is on > 99.981% of the time, for average customer**

Length of outage in area *i*

$$\mathrm{SAIDI} = \frac{\sum_{I} U_i N_i}{\sum_{I} N_i}$$

Number of customers in region *i*

[1] System Average Interruption Duration Index (SAIDI)
http://en.wikipedia.org/wiki/SAIDI

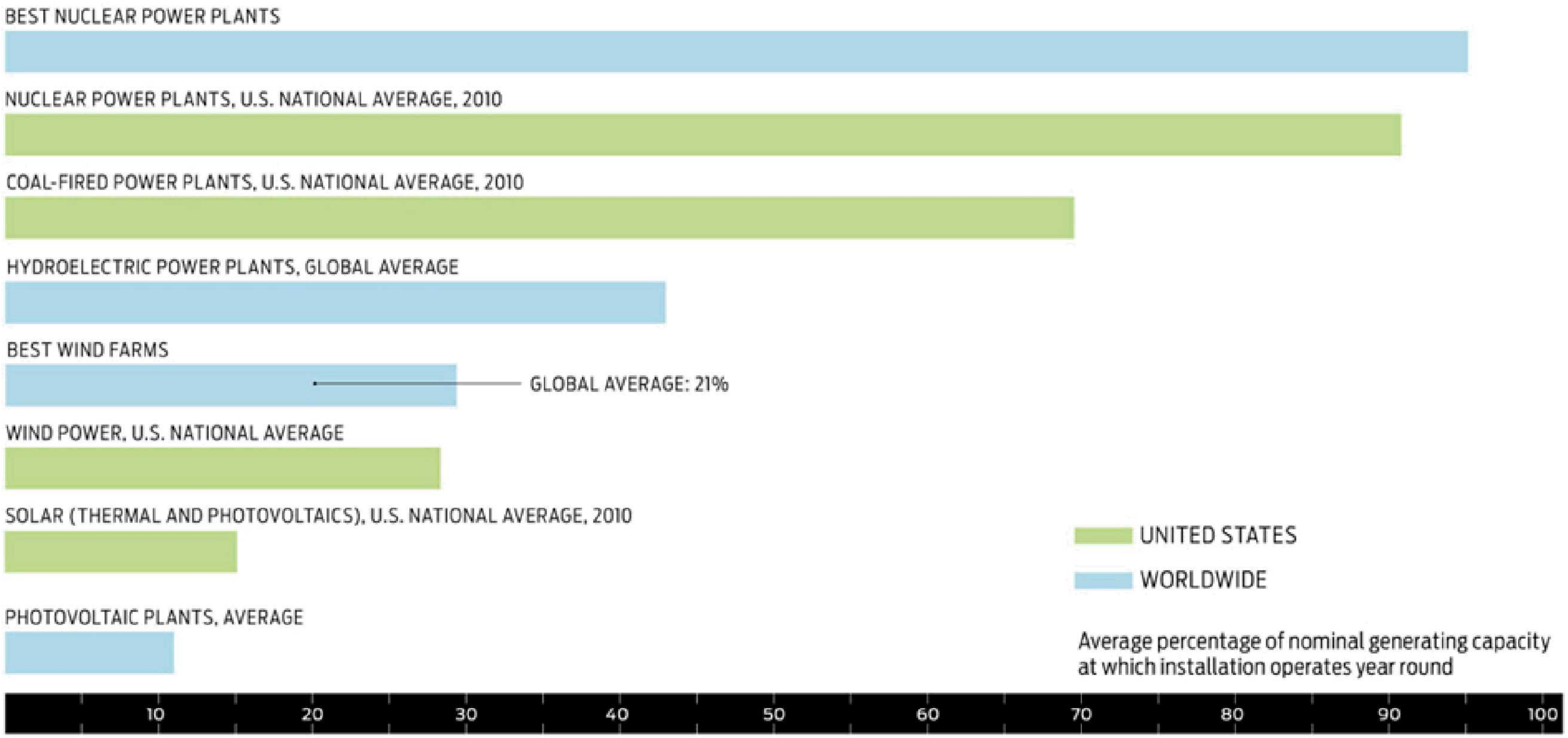
Greater Renewable Penetration is Difficult to Manage

- The Energy (kWh) is there, but many renewables can cause …
  - –Intermittency of power
  - –Variability of power
  - –Reduction in the "stiffness" of the grid

  which may result in …
  - –Frequency and Voltage Fluctuations
  - –Instabilities
  - –Power Outages

Many Renewable Sources are Intermittent and Variable

- **Renewable generation that depends on the weather will vary with the weather**



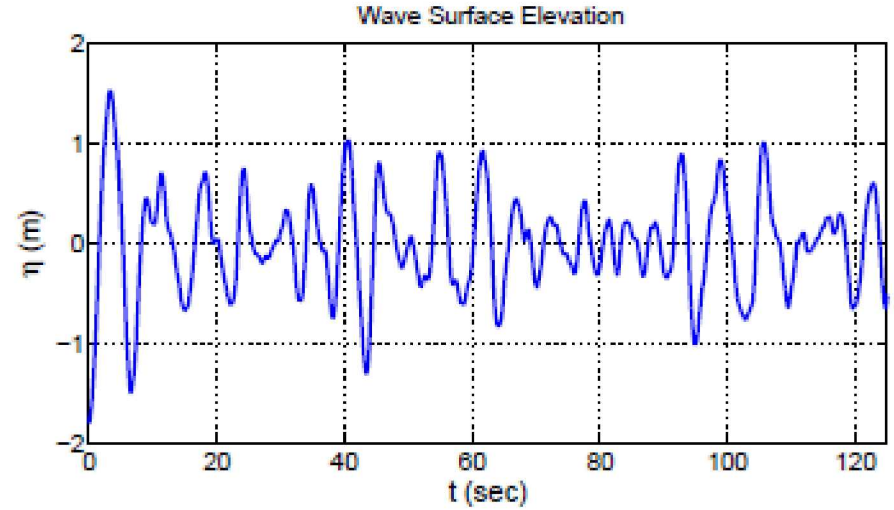
V. Smil; "A Skeptic Looks at Alternative Energy";
IEEE Spectrum Magazine; June 28 2012

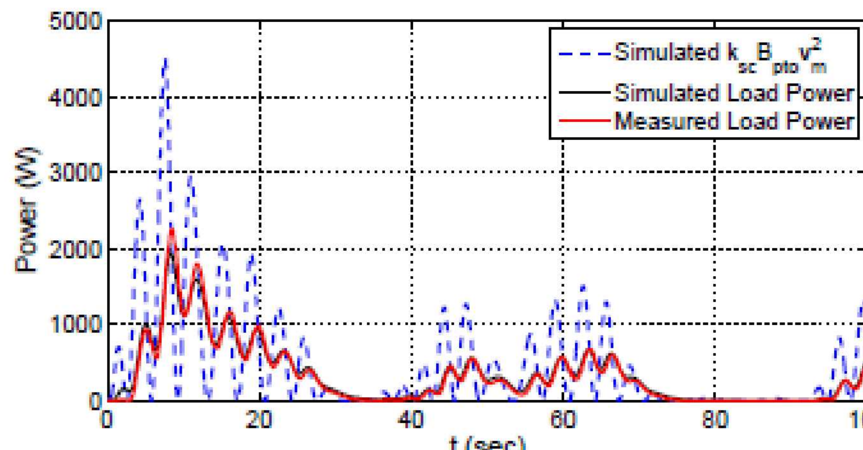
Many Renewable Sources are Intermittent and Variable

- **Renewable generation that depends on the weather will vary with the weather**

Wave Power

J. Neely, K. Ruehl, R. Jepsen, J. Roberts, S. Glover, F. White, M. Horry; "Electromechanical Emulation of Hydrokinetic Generators for Renewable Energy Research"; IEEE OCEANS; San Diego, California; September 23rd-26th 2013.





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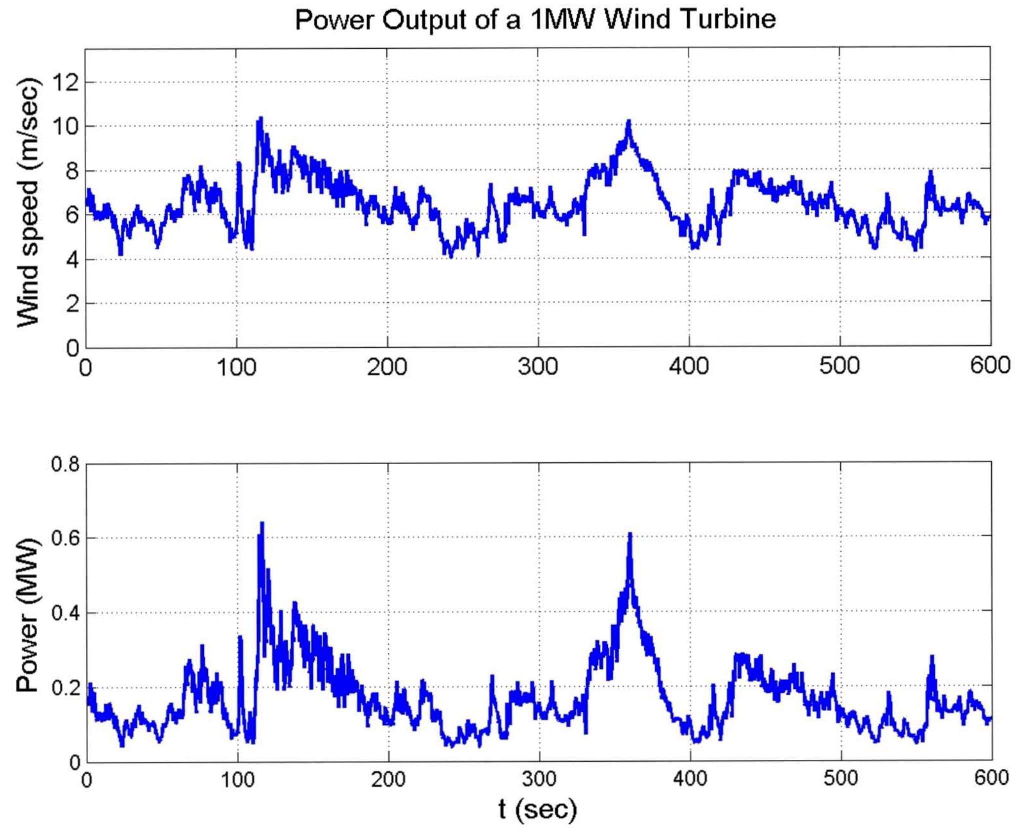
Wind Power



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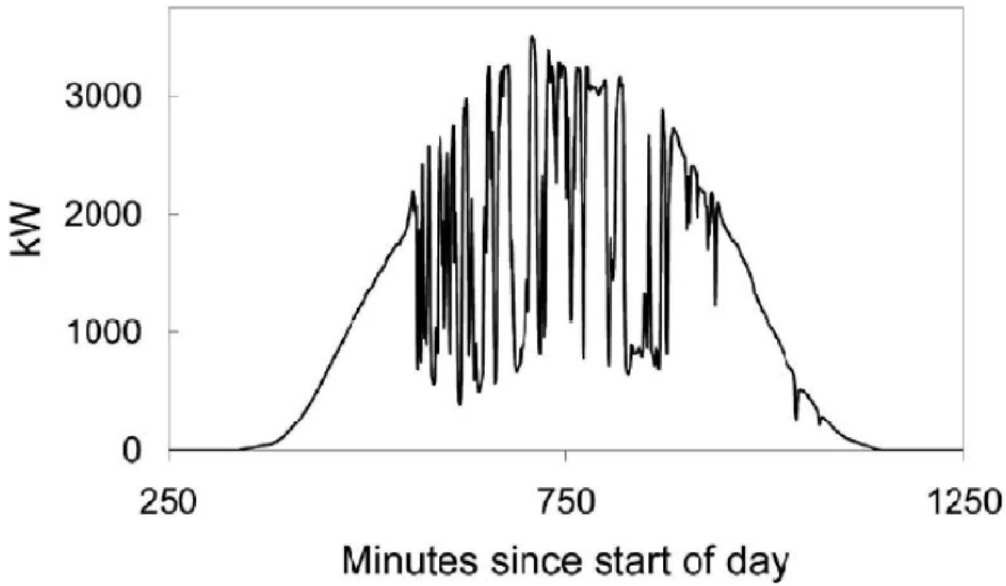
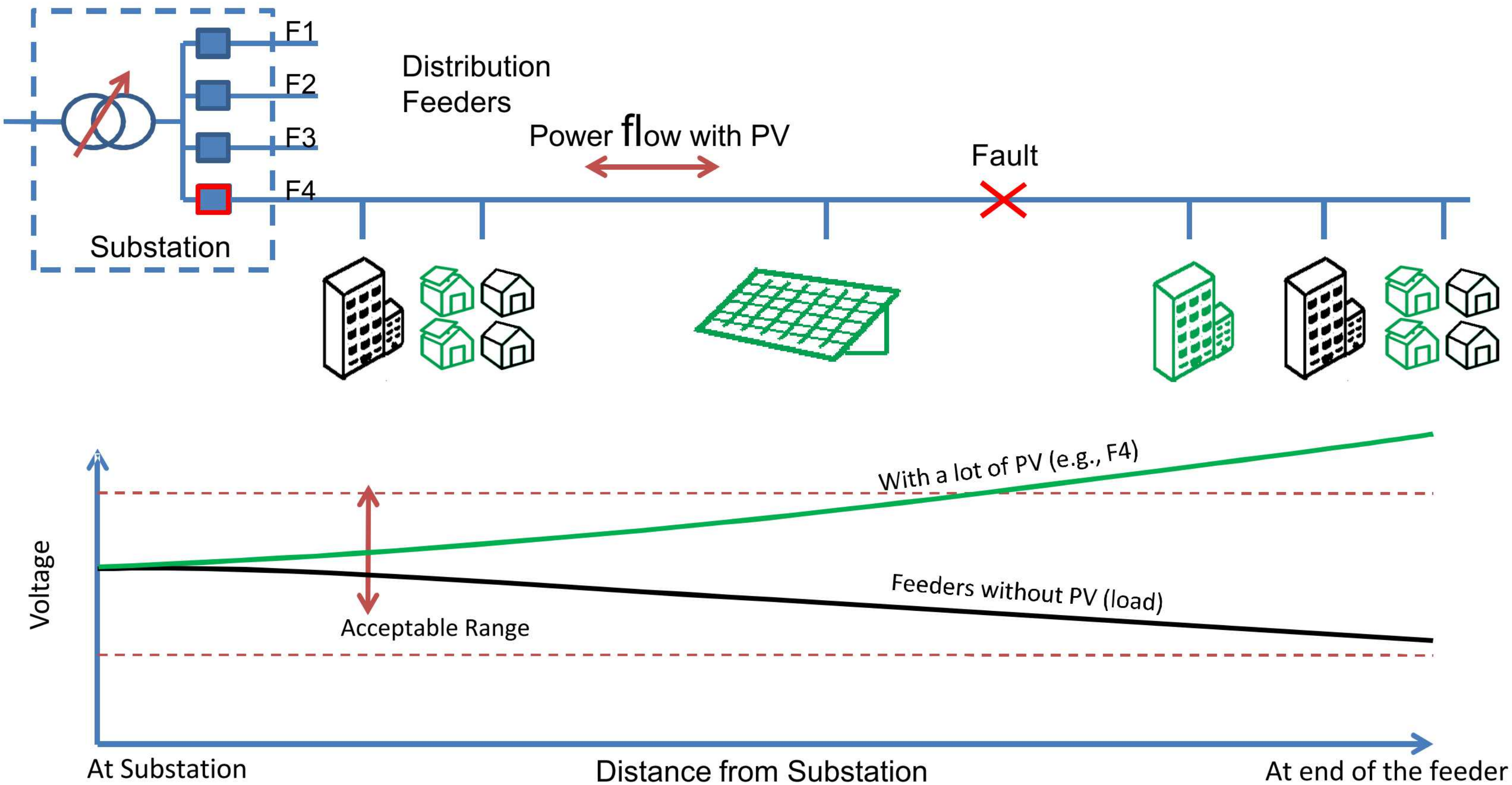
Photovoltaics



Enslin, J. H R, "Network impacts of high penetration of photovoltaic solar power systems," *Power and Energy Society General Meeting, 2010 IEEE* , 25-29 July 2010

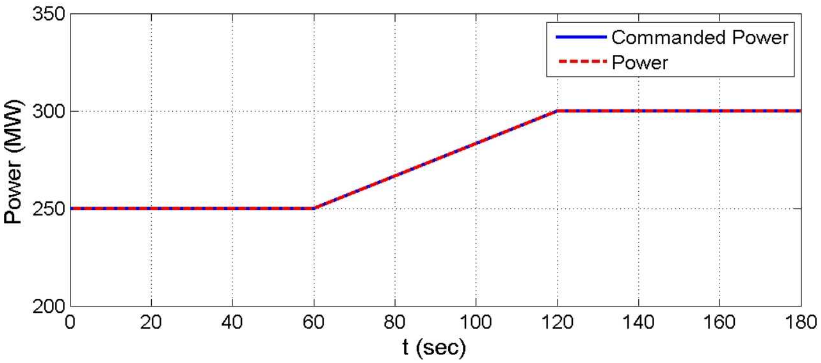
High-Pen PV and grid performance

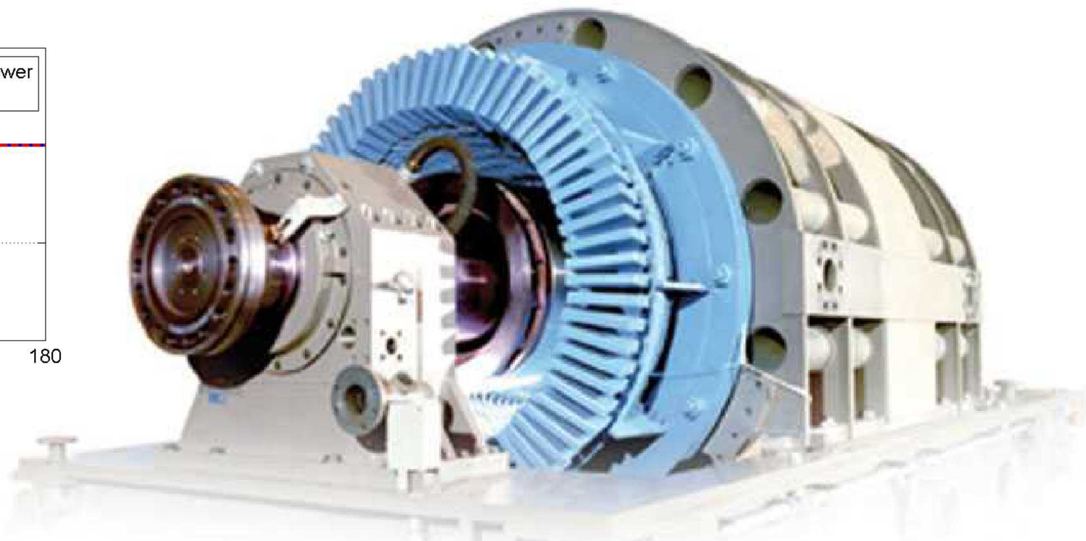
- **PV characteristics (variable, non-dispatchable, inverter-based, distributed) can affect grid performance**
  - **Local voltage control & protection issues tend to emerge first**



Grid Stability Relies on Precise Control of Power Generation and Power Flow

- **Conventional generation is (usually) very good at maintaining power quality/stability**
  - Precise control of output power for frequency regulation
  - Excitation control for voltage regulation

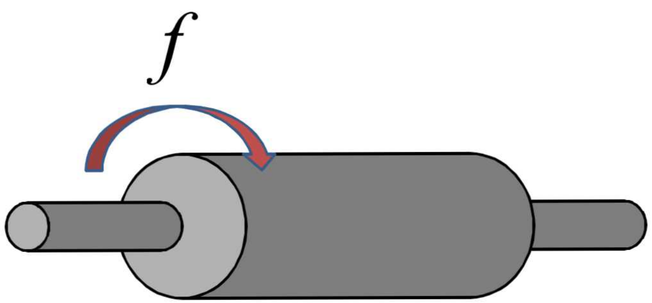




‘Inertia’ Plays a Key Role in Grid Dynamics

- **The grid stores (*some*) kinetic energy in the rotating mass of generators**

$$E_{Kinetic} = \frac{1}{2} J \left(2\pi f\right)^2$$



Increased Variability and Reduced Inertia Increase Frequency Variation

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- **Perturbations in frequency depend on power variation and inertia**
  - Sources and loads are matched in real-time with little "wiggle room" but inertia does store some kinetic energy
  - Reduced system inertia can make system more sensitive to power variation
  - Most distributed PV and Wind is programmed to shutoff with dips in frequency

Variation in source → $\Delta P_{Gen} - \Delta P_{Load}$

$$\Delta f = \frac{\Delta P_{Gen} - \Delta P_{Load}}{4\pi^2 f \cdot J}$$

Inertia → J

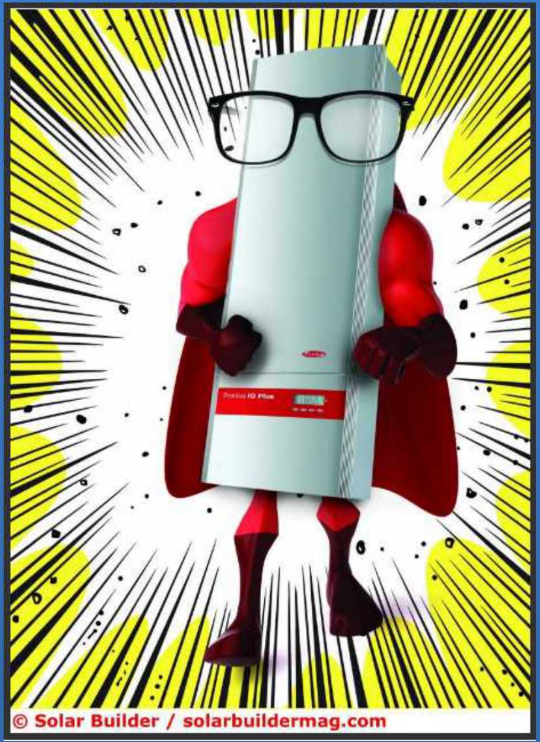
Advanced Inverters for PV Integration

Advanced Inverters Incorporate New Controls to Aid Grid Integration

- **It can become increasingly difficult and expensive to integrate PV at higher and higher penetration levels**

- **A big part of the solution: deployment of advanced inverters in future distribution-connected PV systems**

- **<u>Definition</u> : Advanced inverters…**
  - **Actively support voltage and frequency by modulating the output**
  - **Have high tolerance to grid disturbances**
  - **Interact with the system via communications**



...Faster than a tap changer

...More powerful than a rotating machine

...Able to leap deep voltage sags in a single bound

Courtessy of B. Lydic, Fronius

Functional definitions are in Progress

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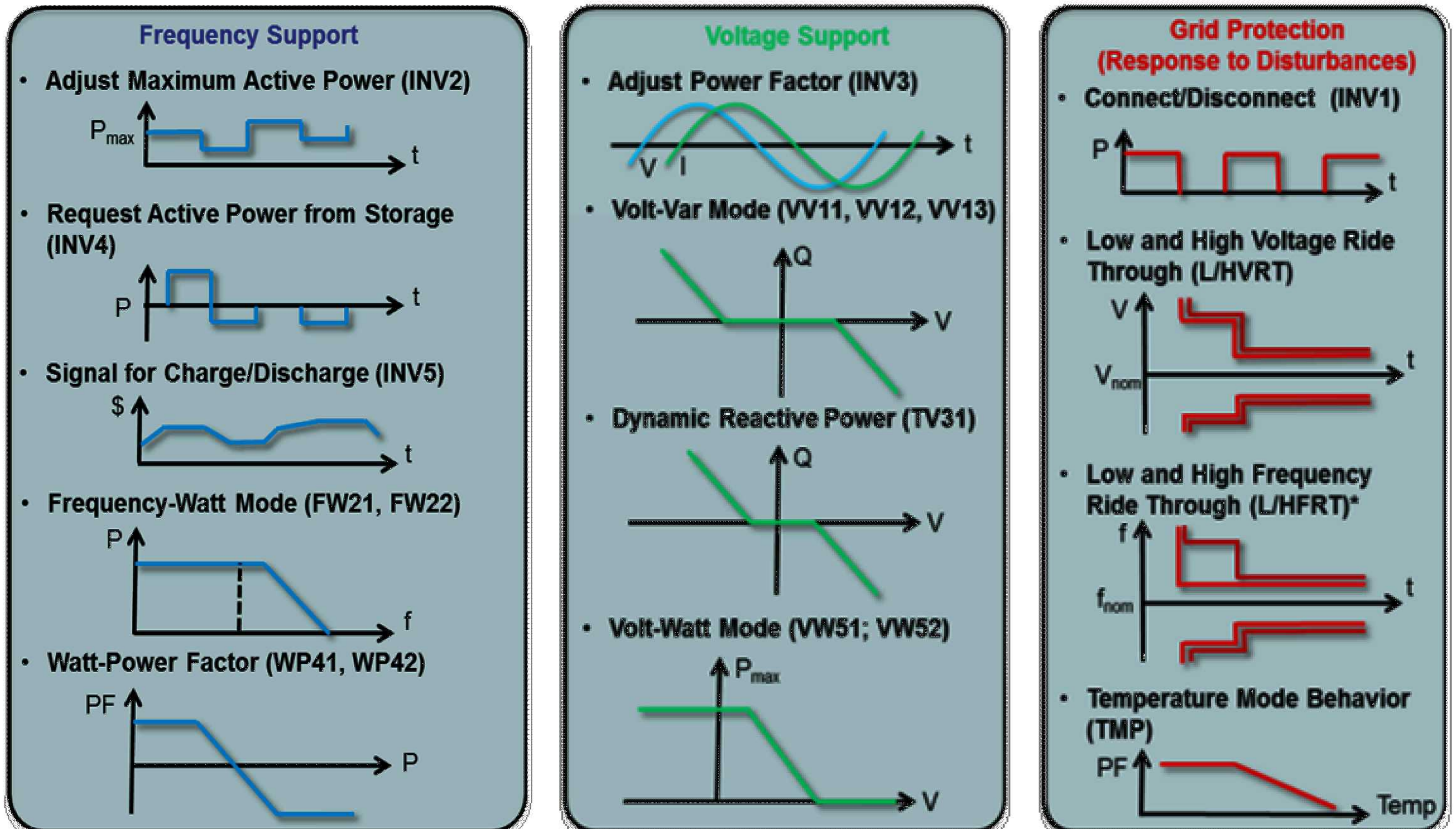
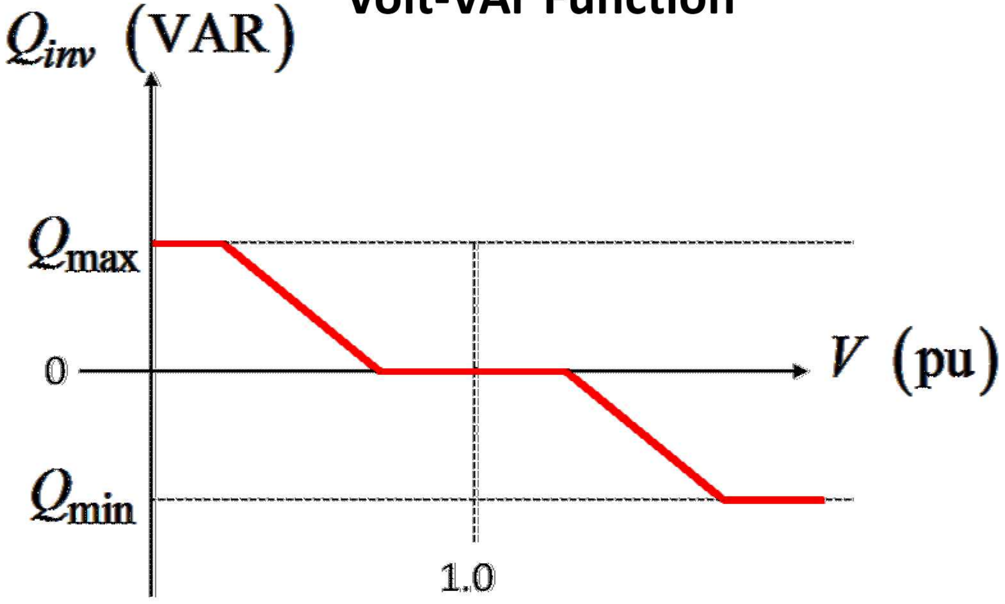
- **Define functions (e.g., Q vs. V) and how they are specified**
- **Functions implemented Autonomously or by Remote Command**
  - Autonomous: Inverter response to local voltage and frequency conditions
  - Commanded: Remote control (e.g., on/off) & configure autonomous behavior



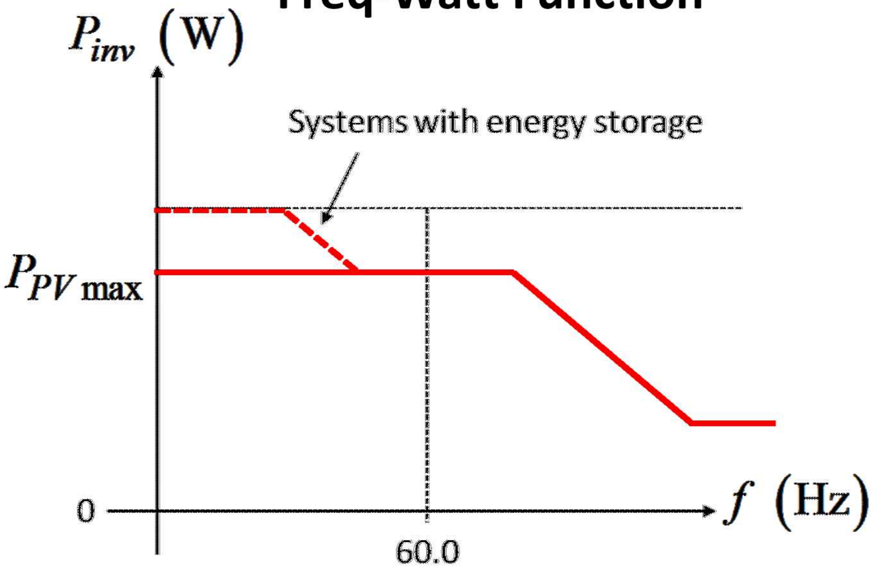
Let's Look Closer at Functions that Mitigate Frequency and Voltage Fluctuation

- **So how do we get Photovoltaics to "look like" generators**
- **Specialized functions monitor system voltage and frequency at grid connection and modulate real and reactive power output**

Volt-VAr Function

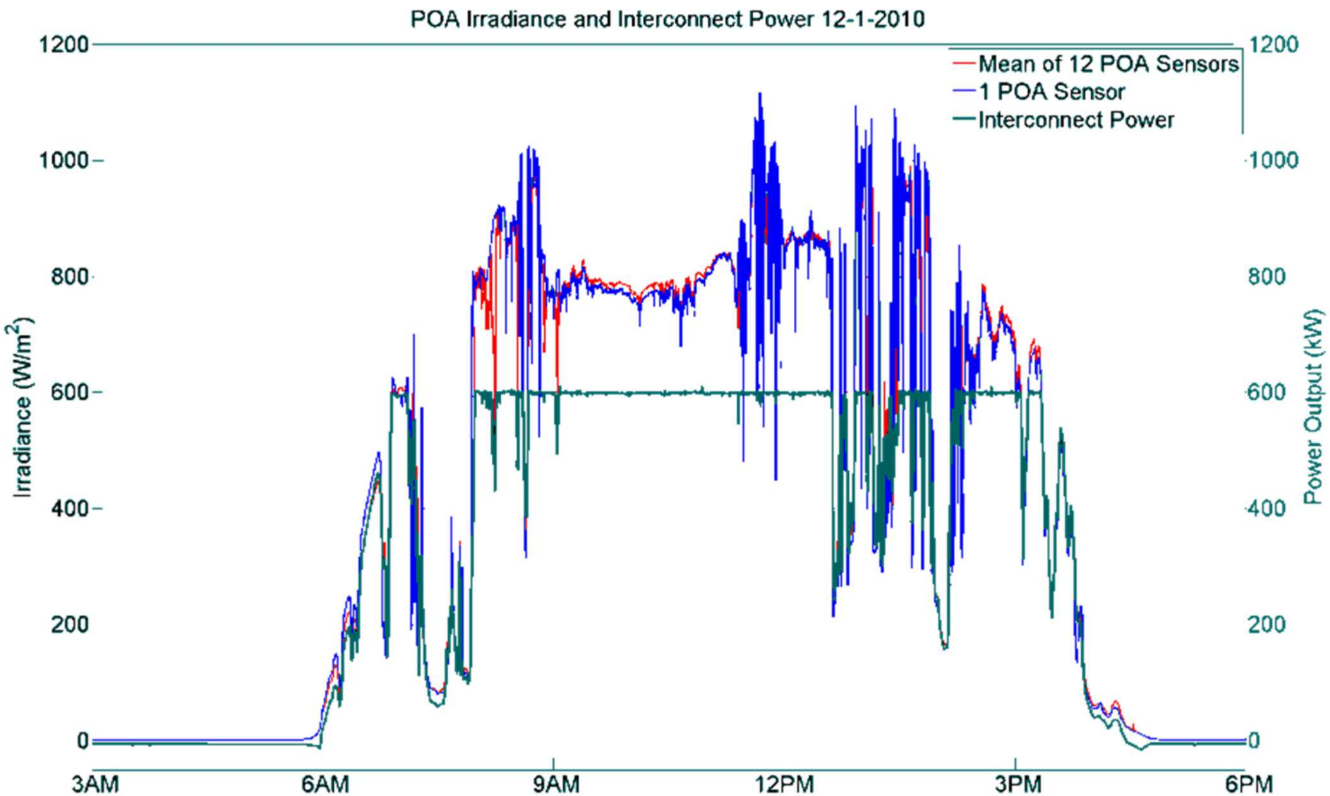


Freq-Watt Function



An Alternative is to Mitigate Variability with Curtailment

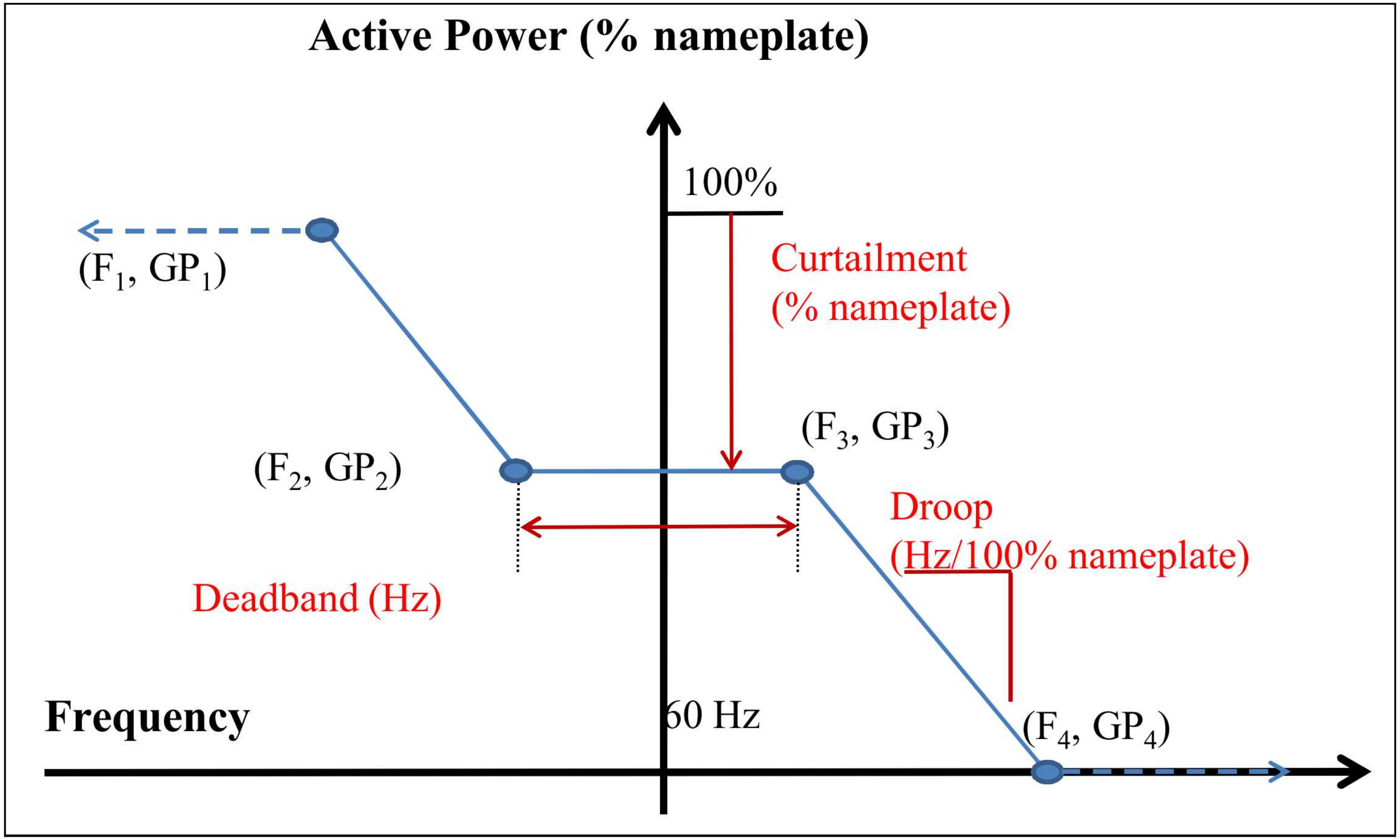
– In previous works, PV system curtailment was used to manage PV variability by reducing PV power ramp rates that affect grid frequency and voltage [1]



[1] J. Johnson, B. Schenkman, J. Quiroz, and A. Ellis, "Initial operating experience of the La Ola 1.2 MW photovoltaic system," Sandia National Laboratories Technical Report SAND2011-8848, 2011.

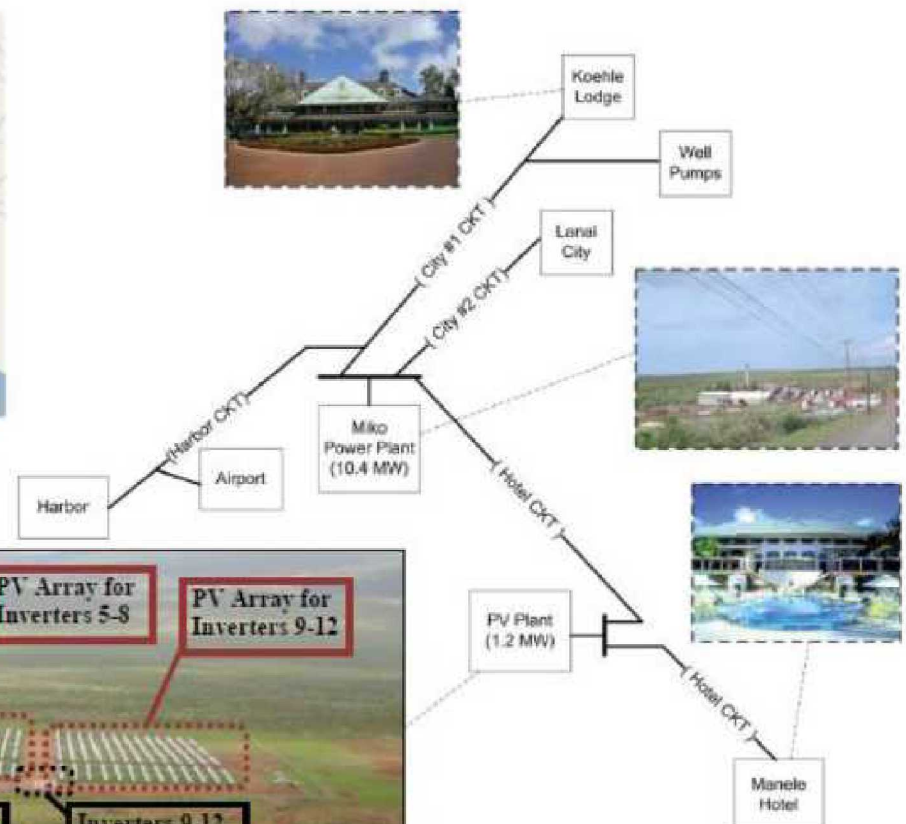
PV Curtailment can Provide Headroom for Under-Frequency Response

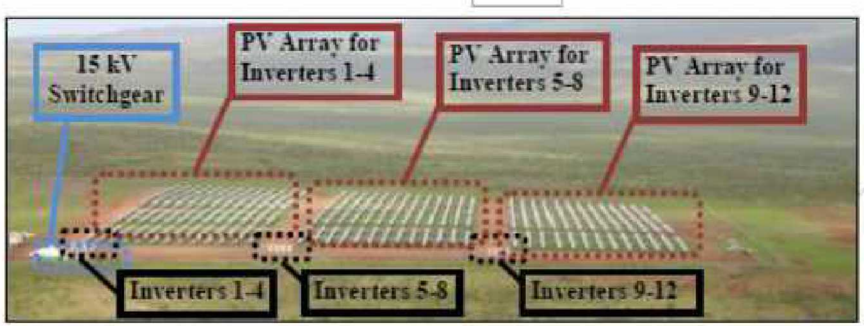
- **In this study, PV power was curtailed to provide "head room", allowing Frequency-Watt functions to respond to over and under frequency events without energy storage**



A Study was Done Focused on the Lana'i Power System

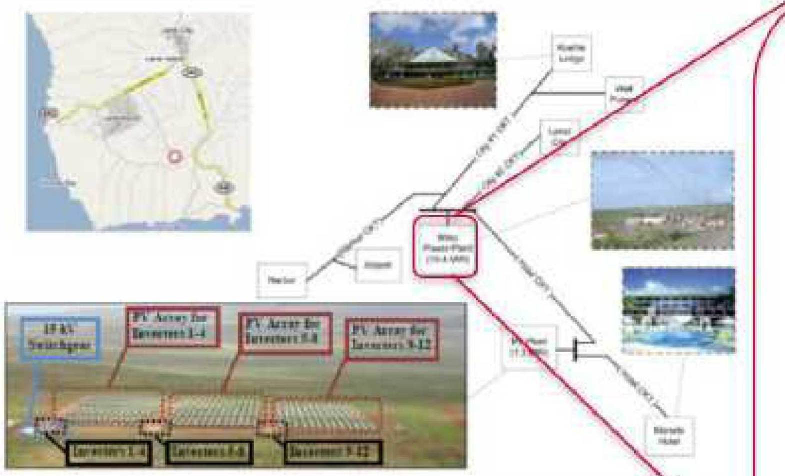
- Island is 140.5 square miles
- 3,200 residents in 1,150 households
- 6 MW peak load
- 10.4 MW diesel power plant, 1.2 MW La Ola PV Power plant
- Characterized by high solar variability

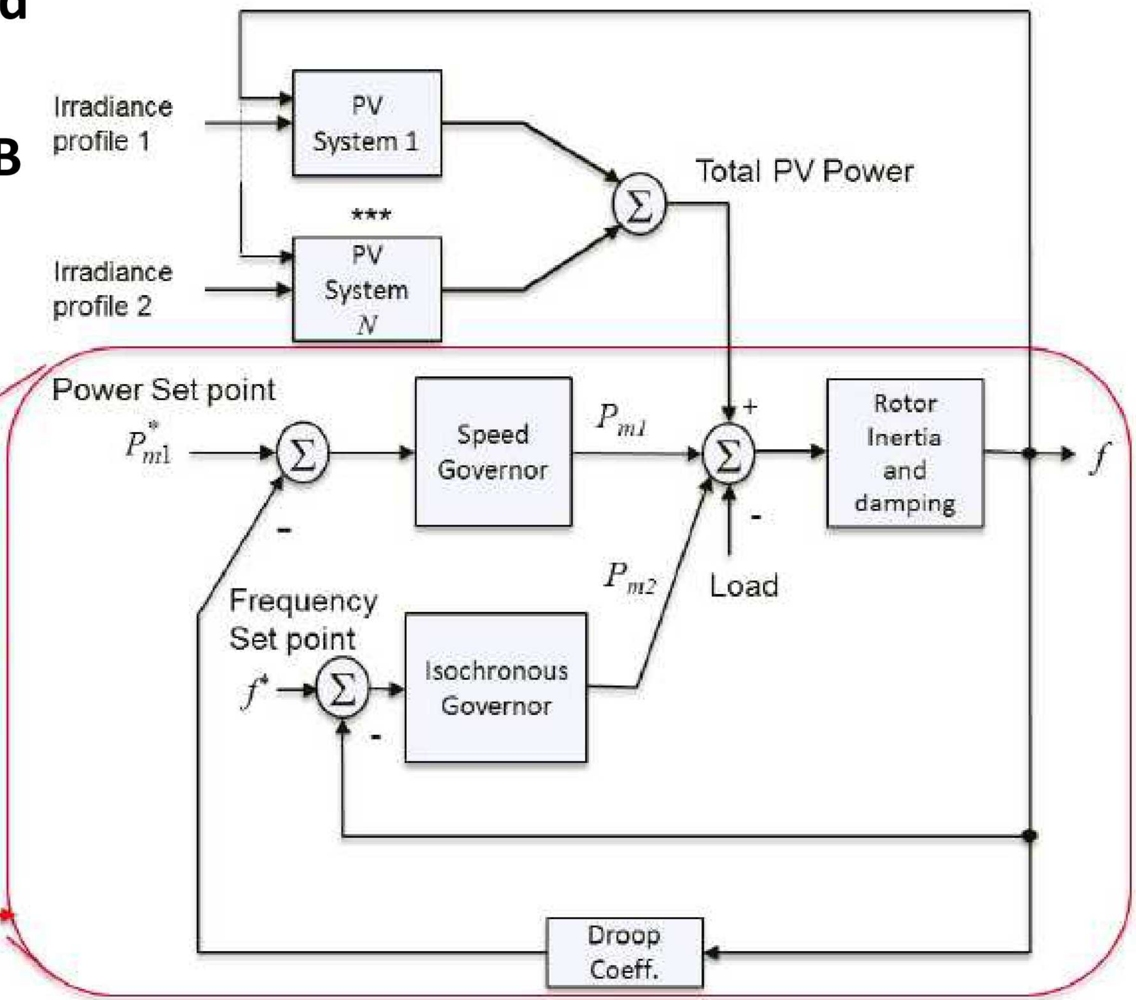




Simplified Lana'i Power System Model Allows Day-Long Simulations

- Generation was summed and aggregated
- System simulated in MATLAB from sunrise to sundown

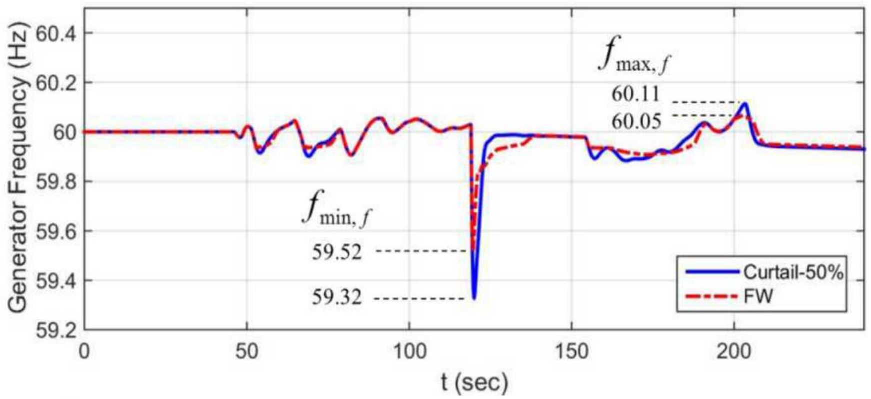


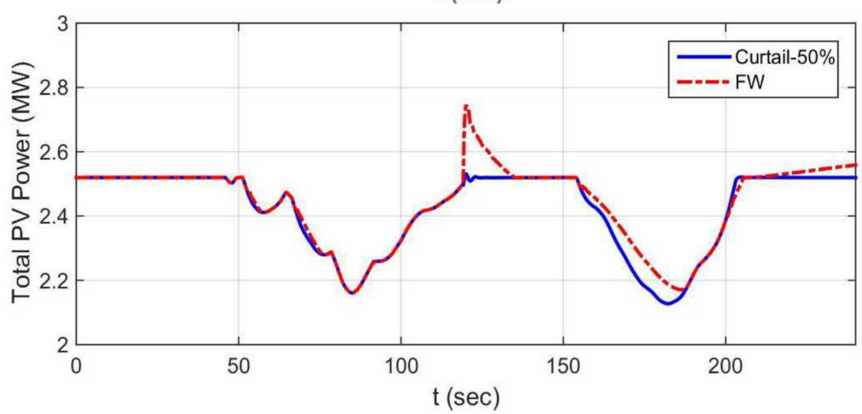


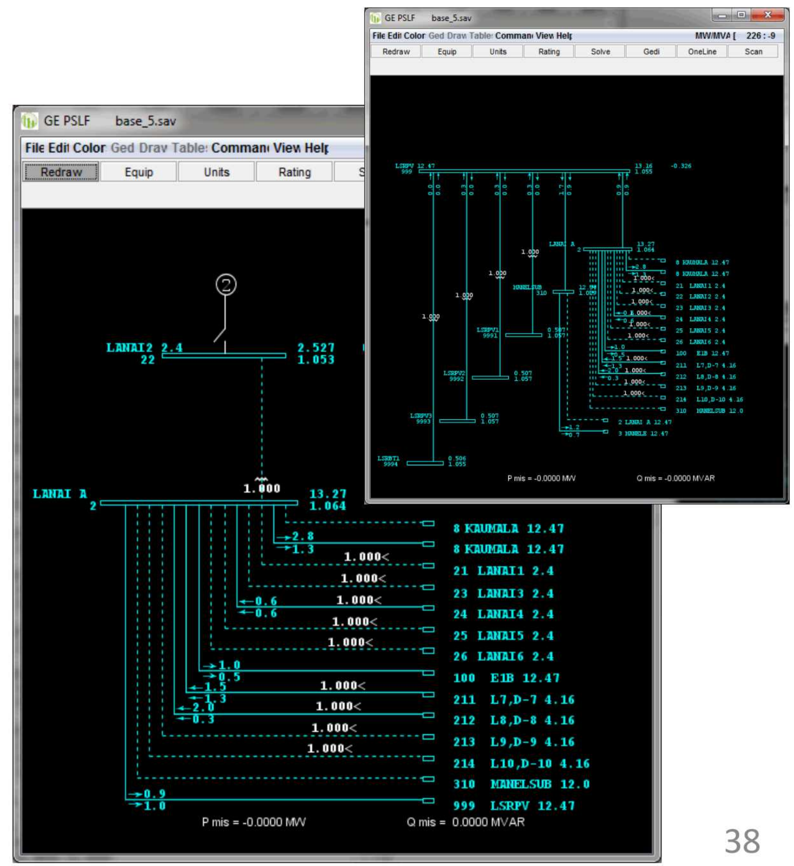
Power Plant Simplified Model

High Fidelity Lana'i Power System Model Enables Contingency Simulation

– **Lana'i power system was modeled in GE's Positive Sequence Load Flow (PSLF)**
– **System simulated for 4 minutes with contingency events**
  - *Line Fault*
  - *Loss of Synchronous Generator*

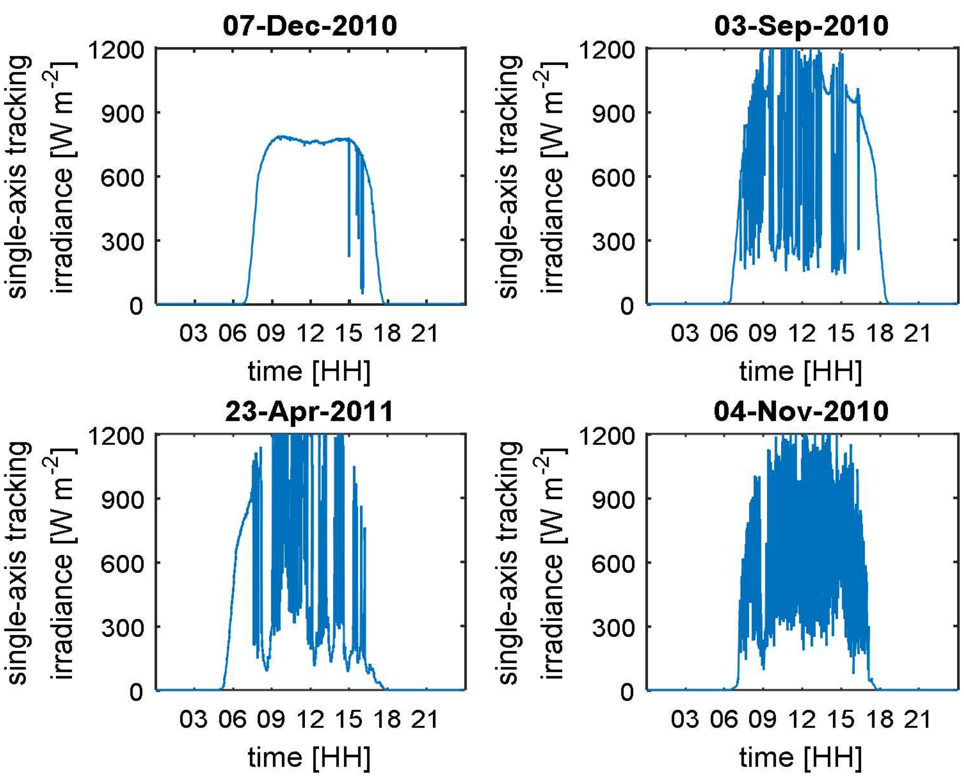




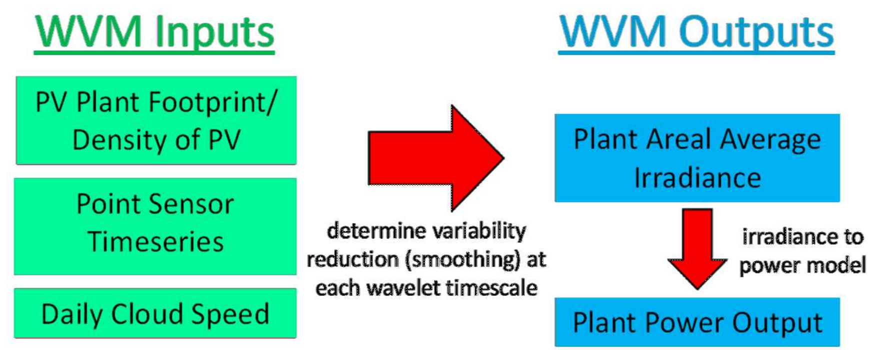


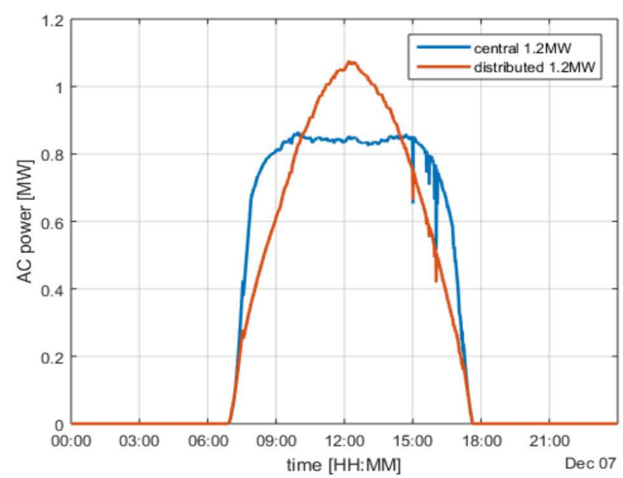
Irradiance Data from La Ola PV Plant used to Compute Available PV power

- Four datasets were selected
  - *Lowest variability – December 7th, 2010*
  - *'Average' variability – September 3rd, 2010*
  - *Highest Single Ramp rate – April 23rd, 2011*
  - *Highest variability – November 4th, 2010*



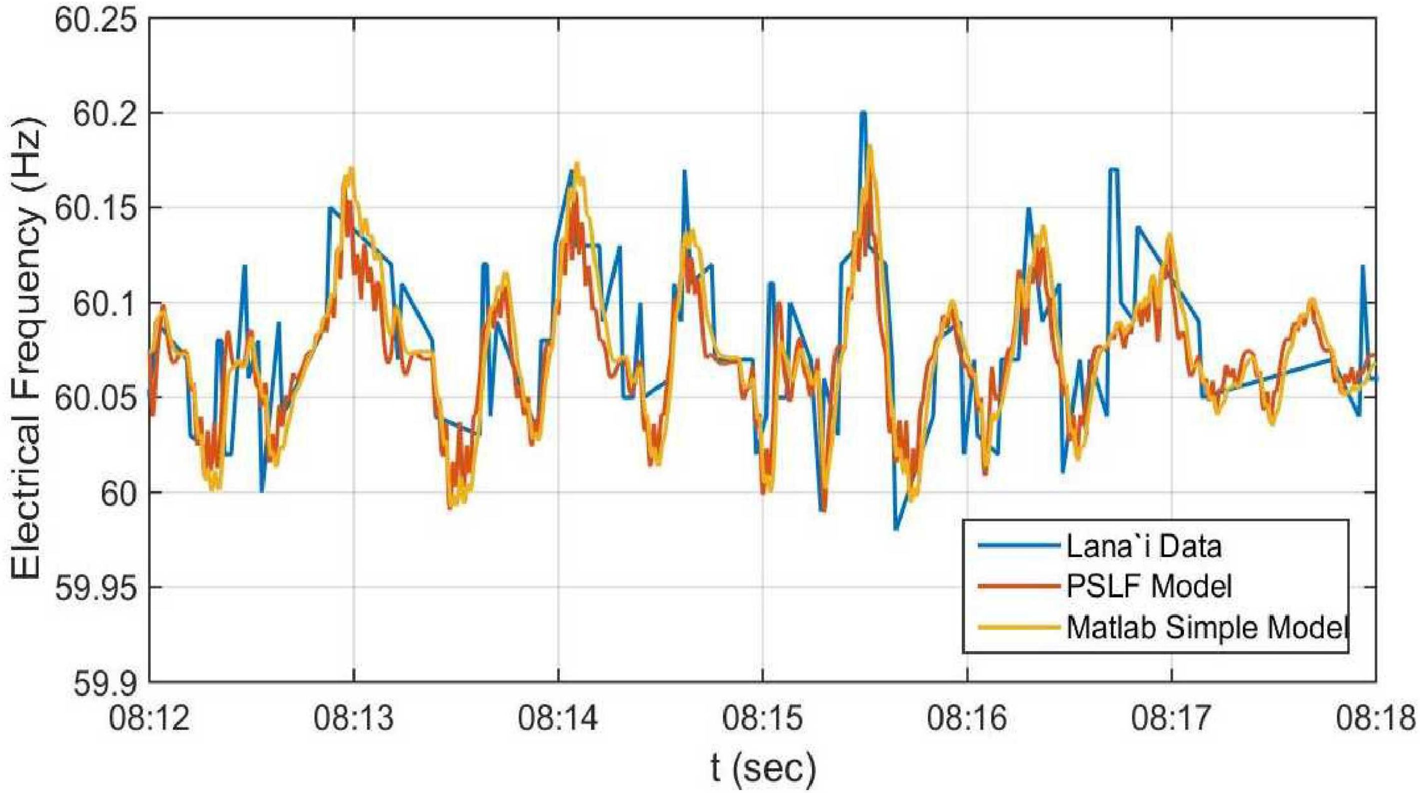
- Available PV power computed using Sandia Models
  - *Sandia Wavelet Variability Model*
  - *Sandia Array Performance Model*
  - *Tracker and rooftop*





Both Models were Validated using Data from La Ola PV Plant

- An OSIsoft PI server contains time-synchronized PV power and frequency data
- A period of high PV variability was replayed in both the simplified MATLAB model and the PSLF system model to generate simulated grid frequency
- Simulated and modeled frequency responses were compared



PV Variability and Geographic Diversity were Included in System Models

– To increase PV penetration in the model, new systems were "installed"

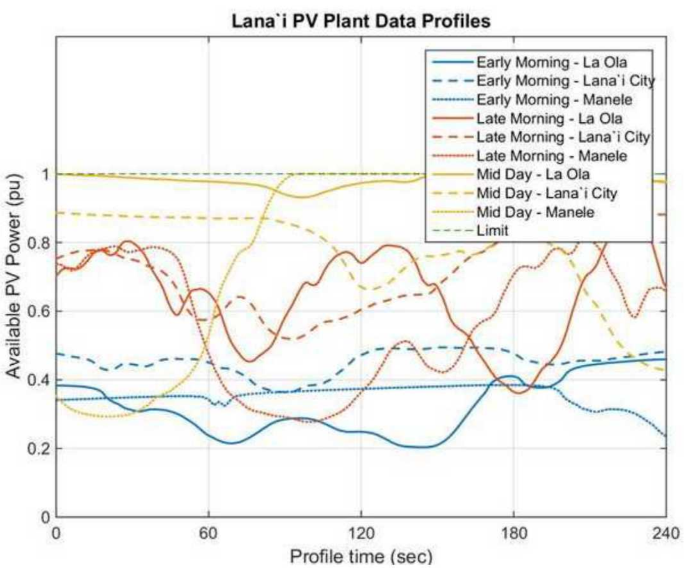
– Using realistic assumptions of cloud motion, La Ola data was time-shifted to enable varying PV power in different locations

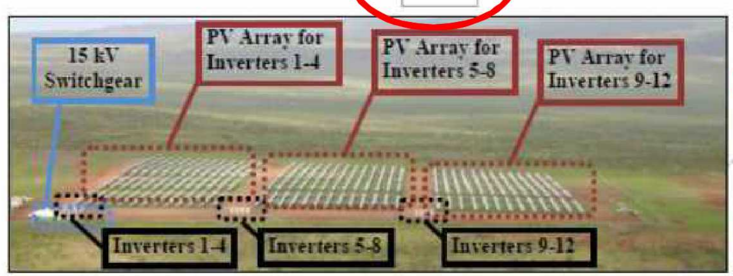
PV scenarios considered PV Penetration, Type, Time of day

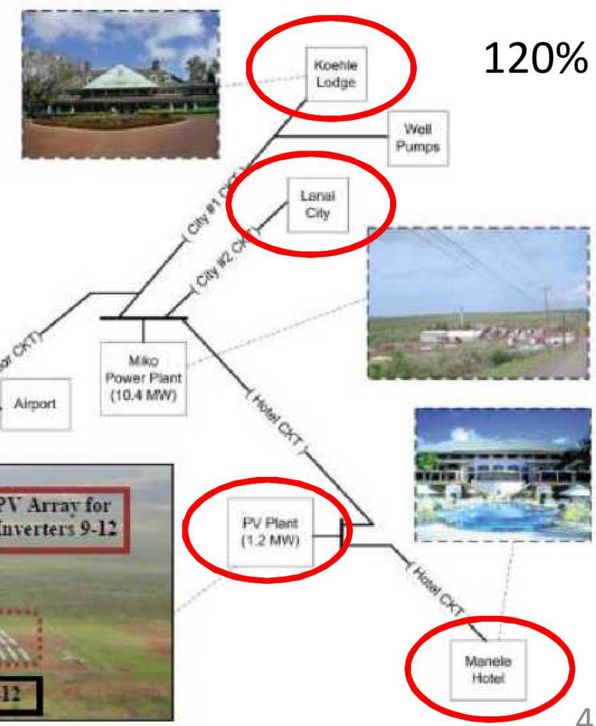
20%

70%

120%

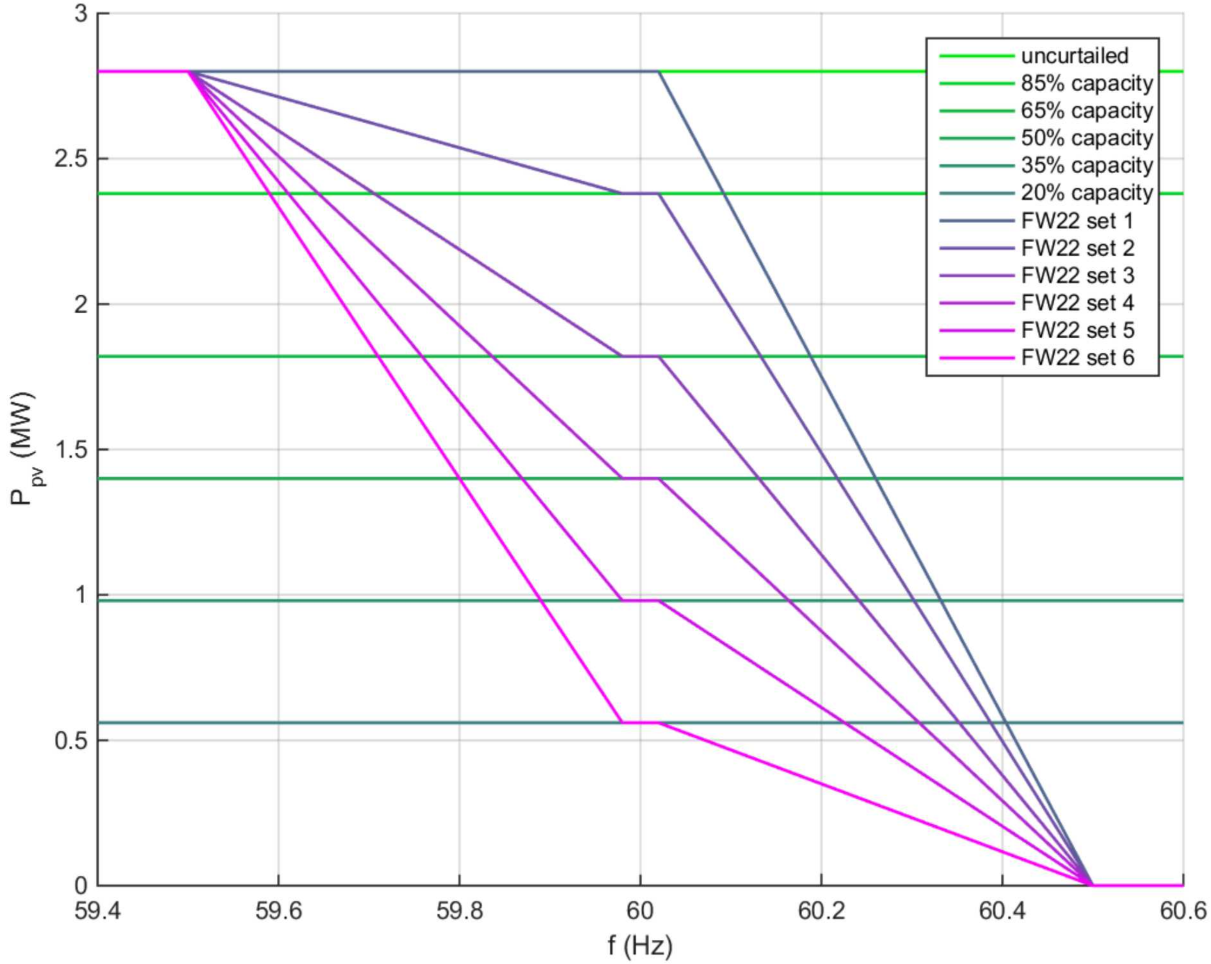






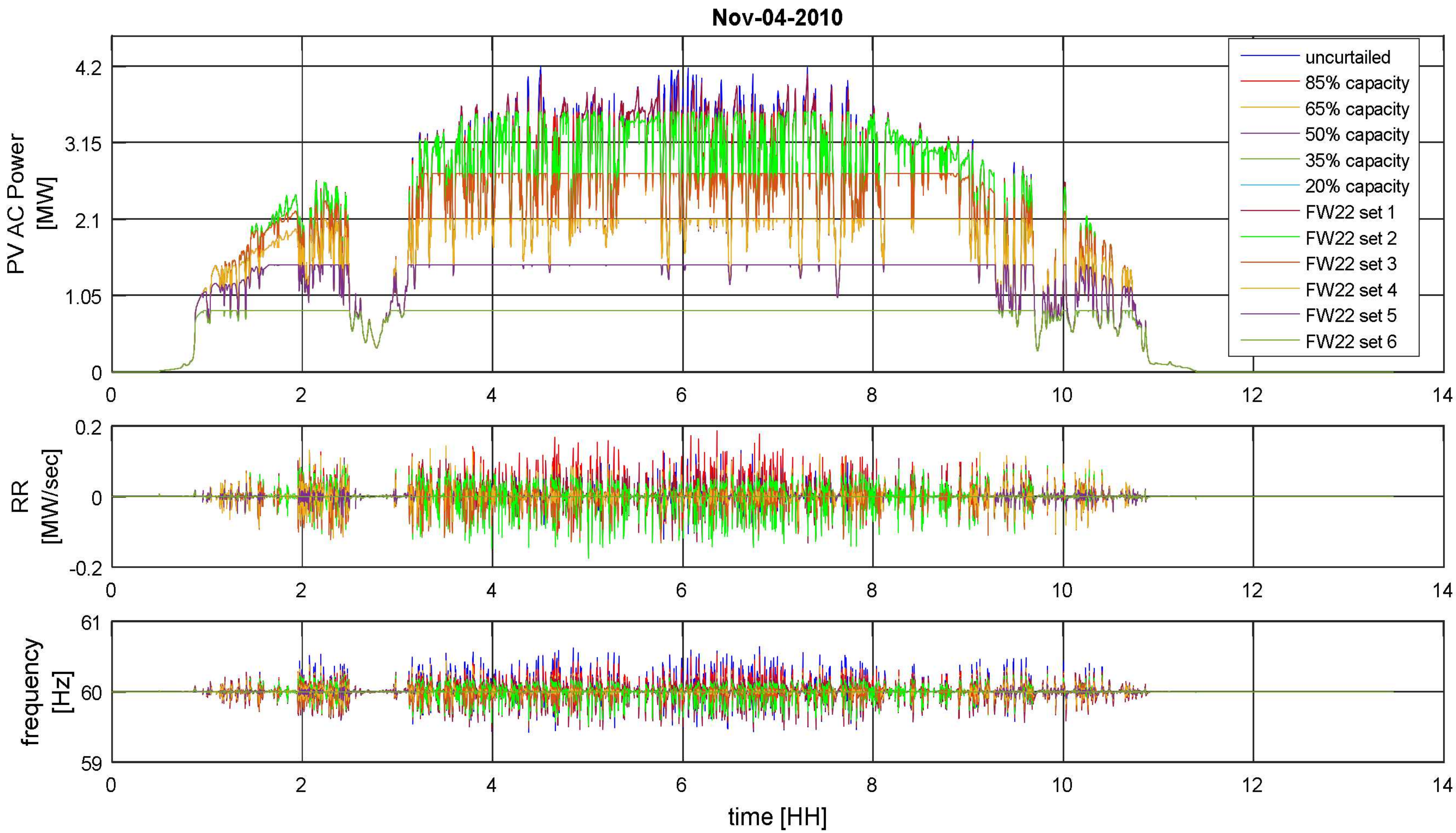
Simulation Studies Included Several Frequency-Watt Settings

– Simulation studies were done on both models with 6 Frequency-Watt definitions, 5 capacity curtailment settings, and an uncurtailed/uncontrolled case



Energy versus Performance Outcomes were Compared in MATLAB

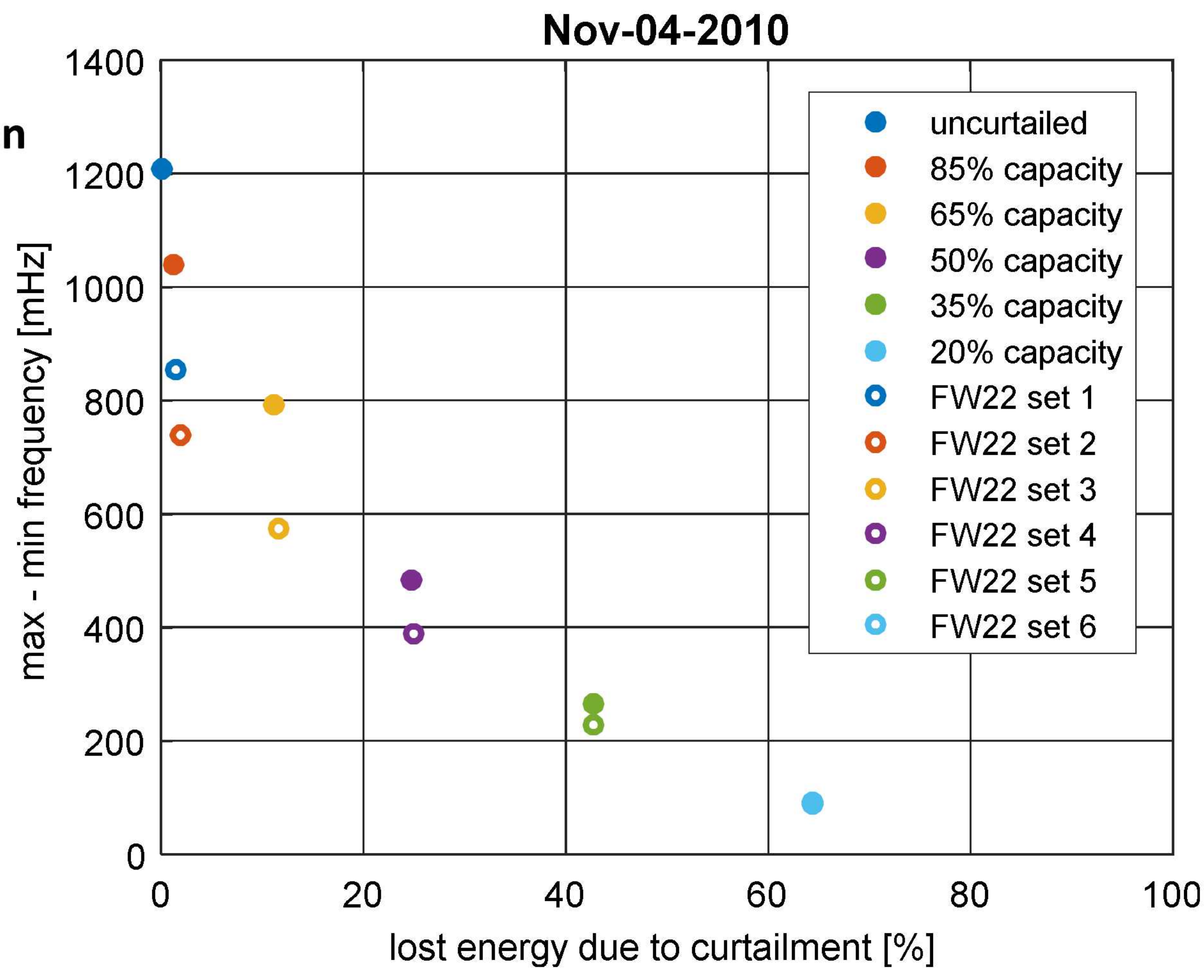
– Simulation studies were done in MATLAB with 6 Frequency-Watt definitions, 5 capacity curtailment settings, and an uncurtailed/uncontrolled case



Energy versus Performance Outcomes were Compared in MATLAB

– Simulation studies were done in MATLAB with 6 Frequency-Watt definitions, 5 capacity curtailment settings, and an uncurtailed/uncontrolled case

70% penetration

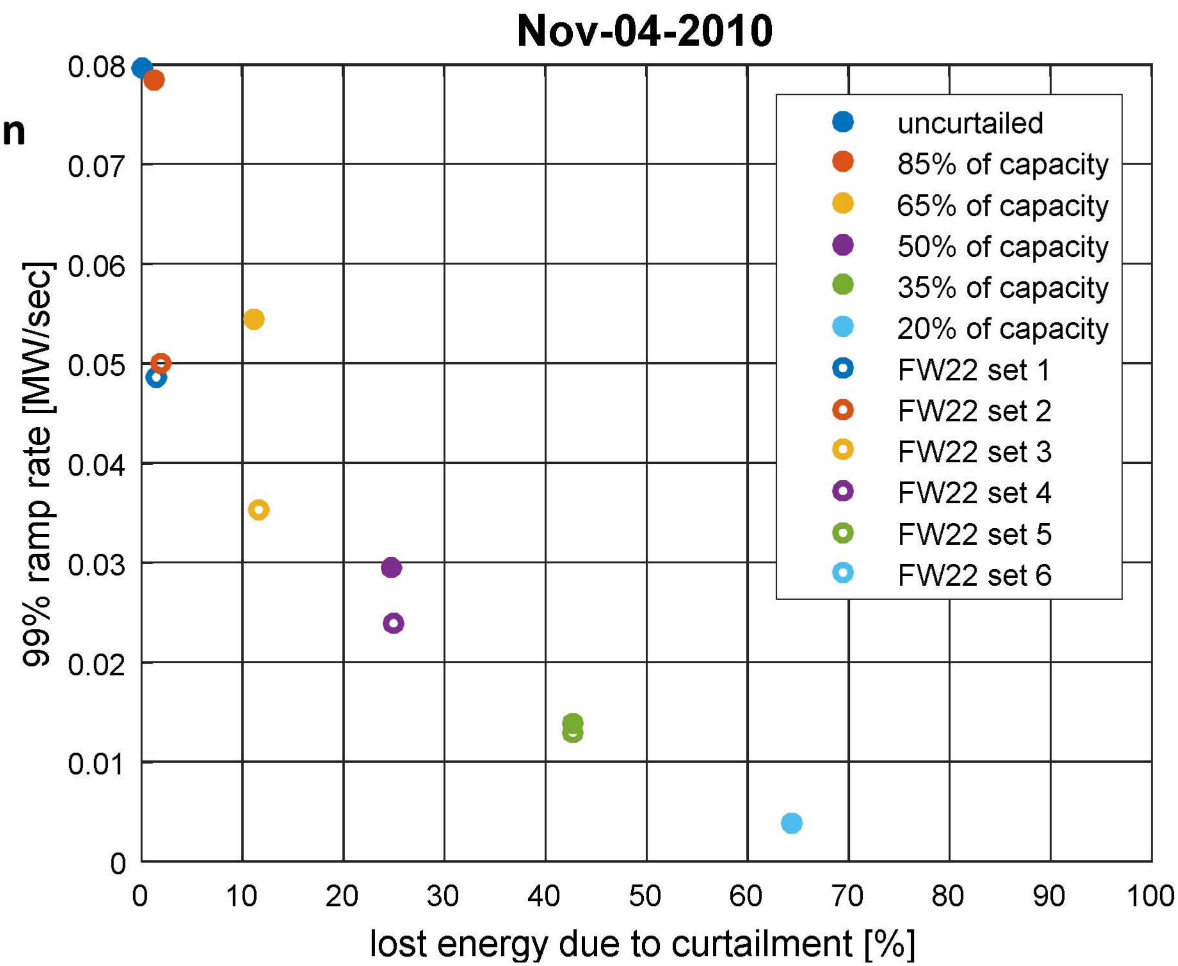


Frequency deviations are only due to PV variability

Energy versus Performance Outcomes were Compared in MATLAB

– By responding to frequency with negative feedback, an improvement is also seen in the PV Power Ramp Rate

70% penetration

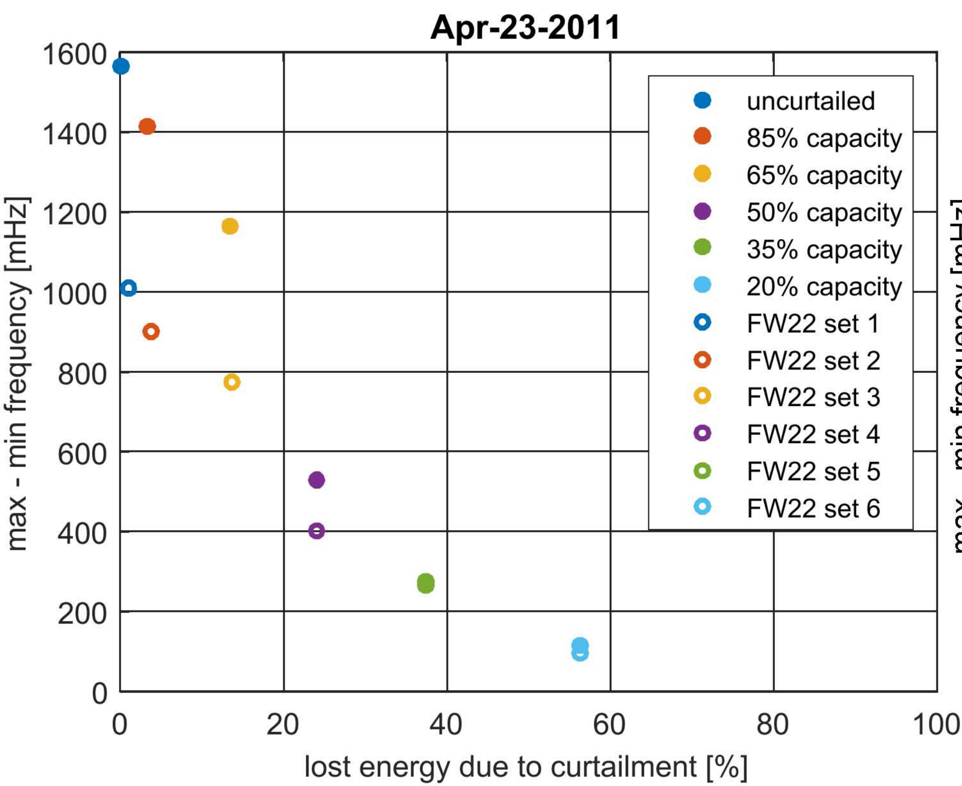


Ramp Rates are only due to PV variability

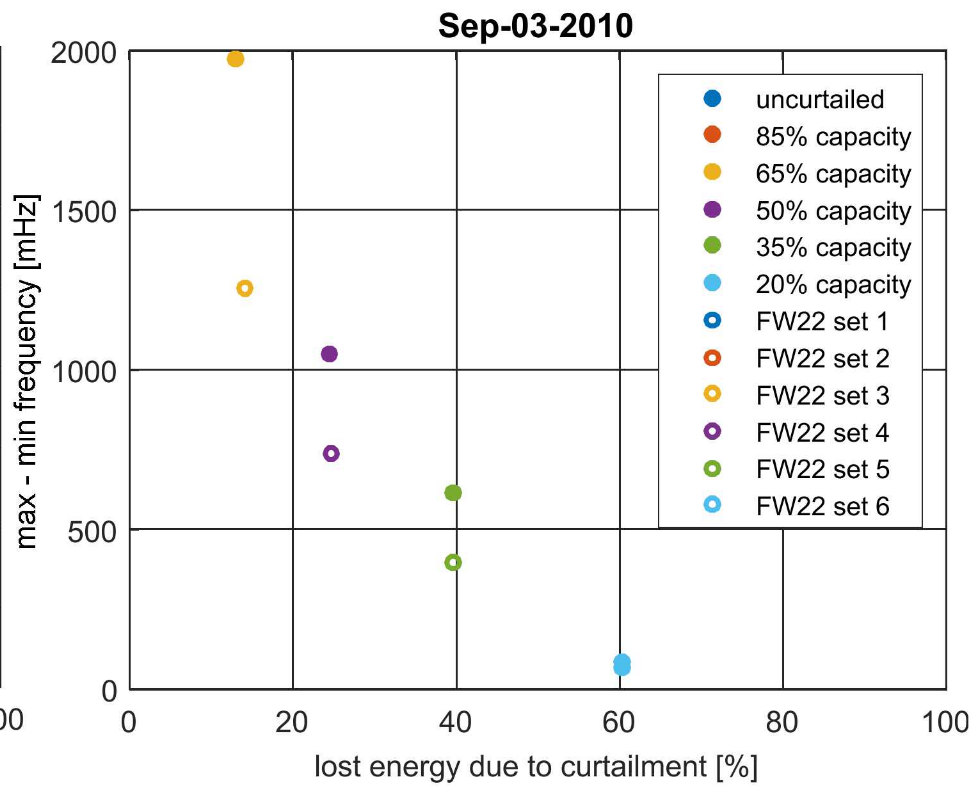
Energy versus Performance Outcomes were Compared in MATLAB

- Similar improvements are seen in other datasets, and results vary

70% penetration

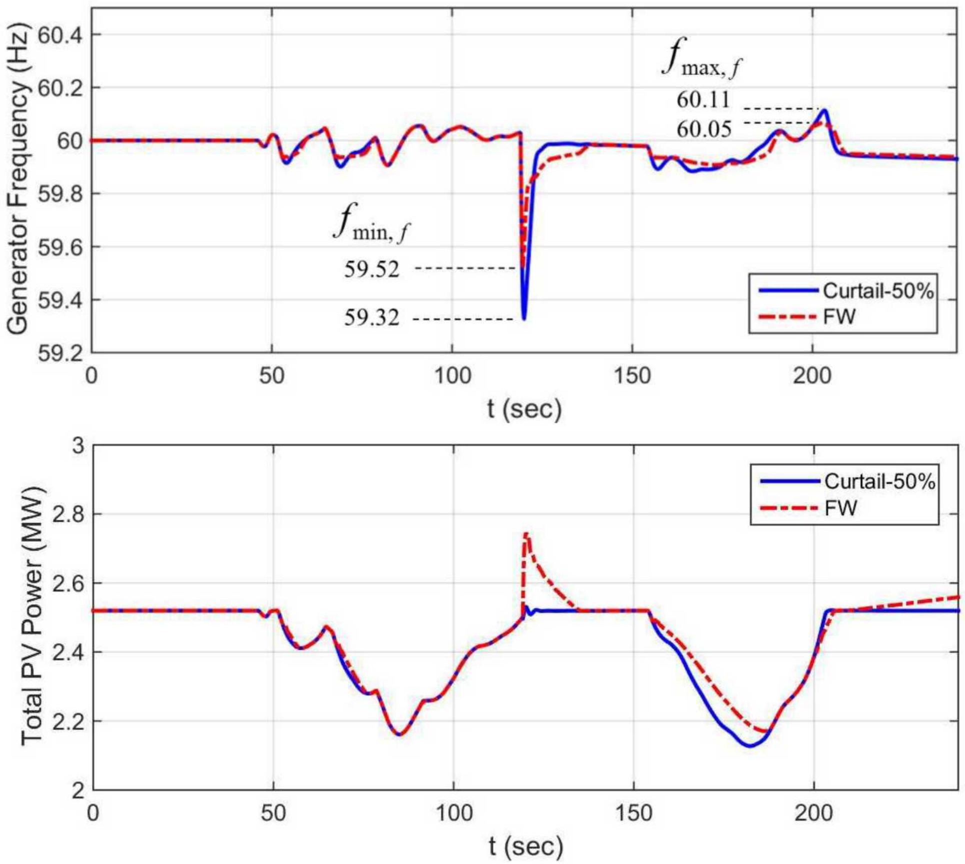


120% penetration

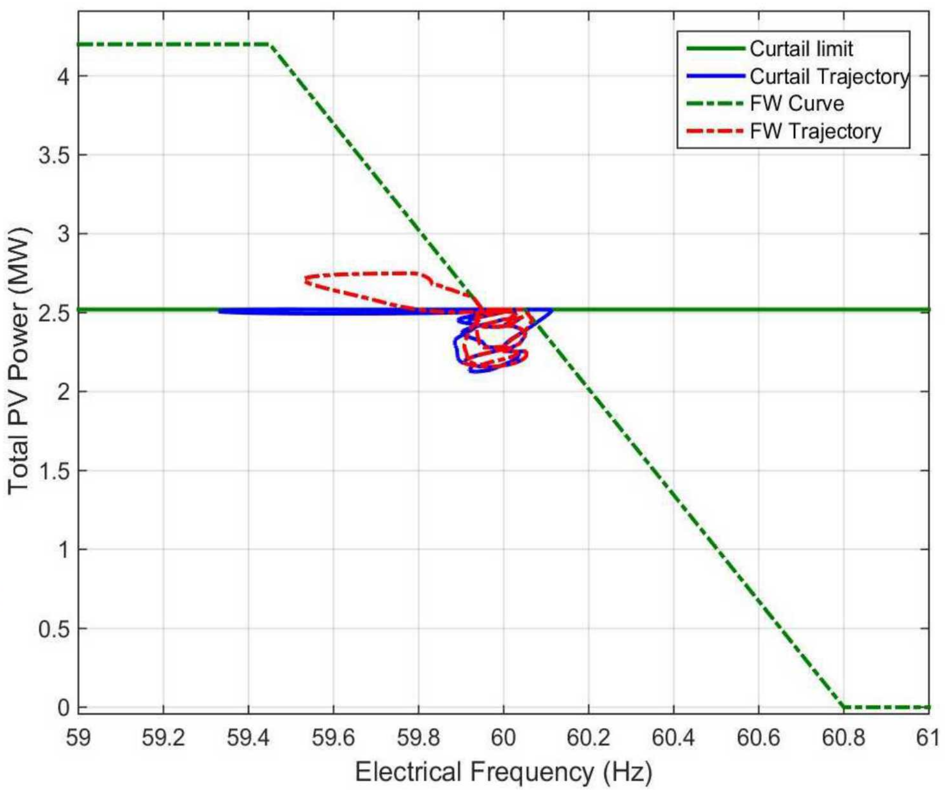


Dynamic Response following an 'Event' was Evaluated in PSLF

– Frequency Nadir is compared with and without Frequency-Watt deployment following a loss of generation (i.e. Synchronous generator trips offline)

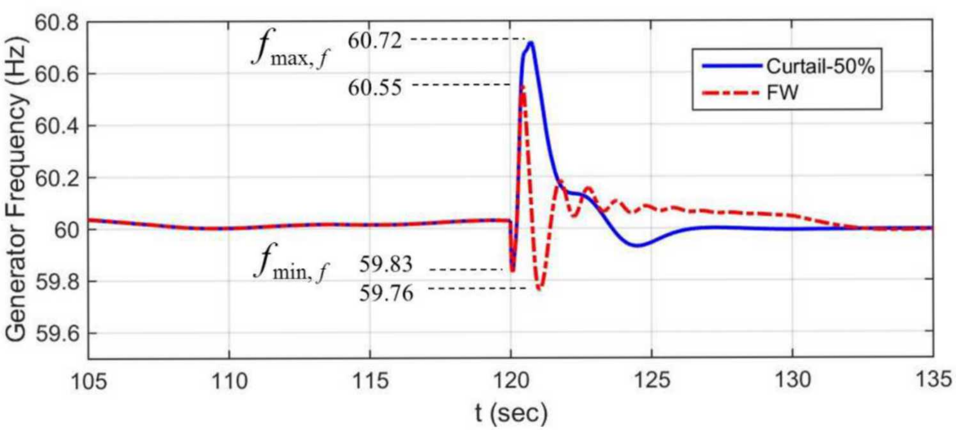


Frequency vs. Power

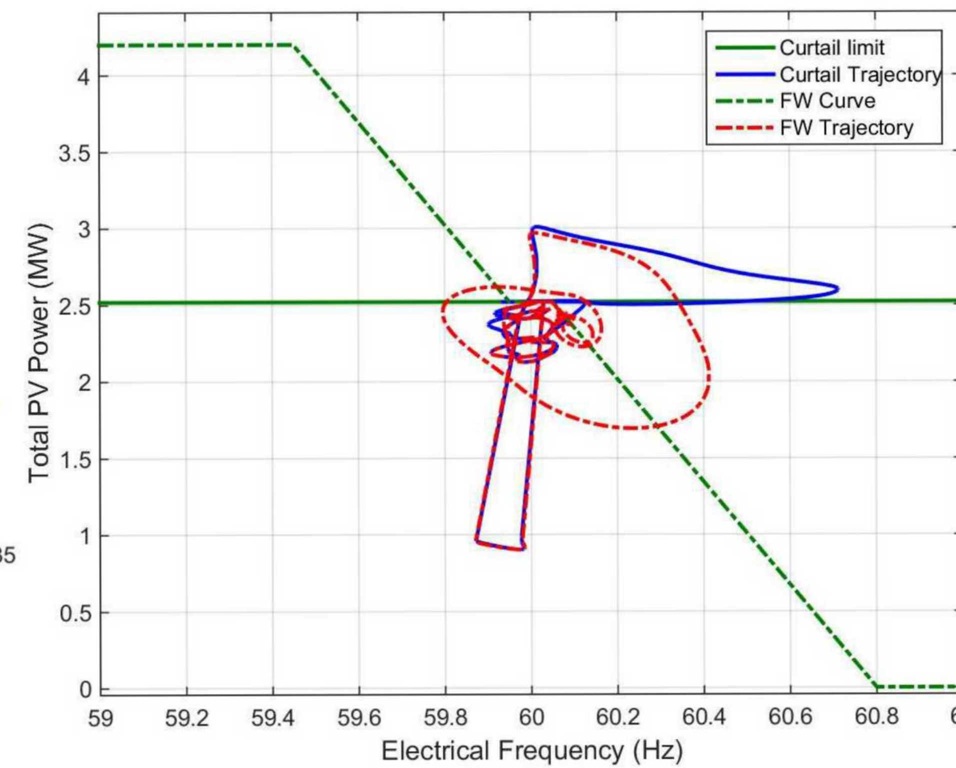


Dynamic Response following an 'Event' was Evaluated in PSLF

– Frequency rise is compared with and without Frequency-Watt deployment following a line fault

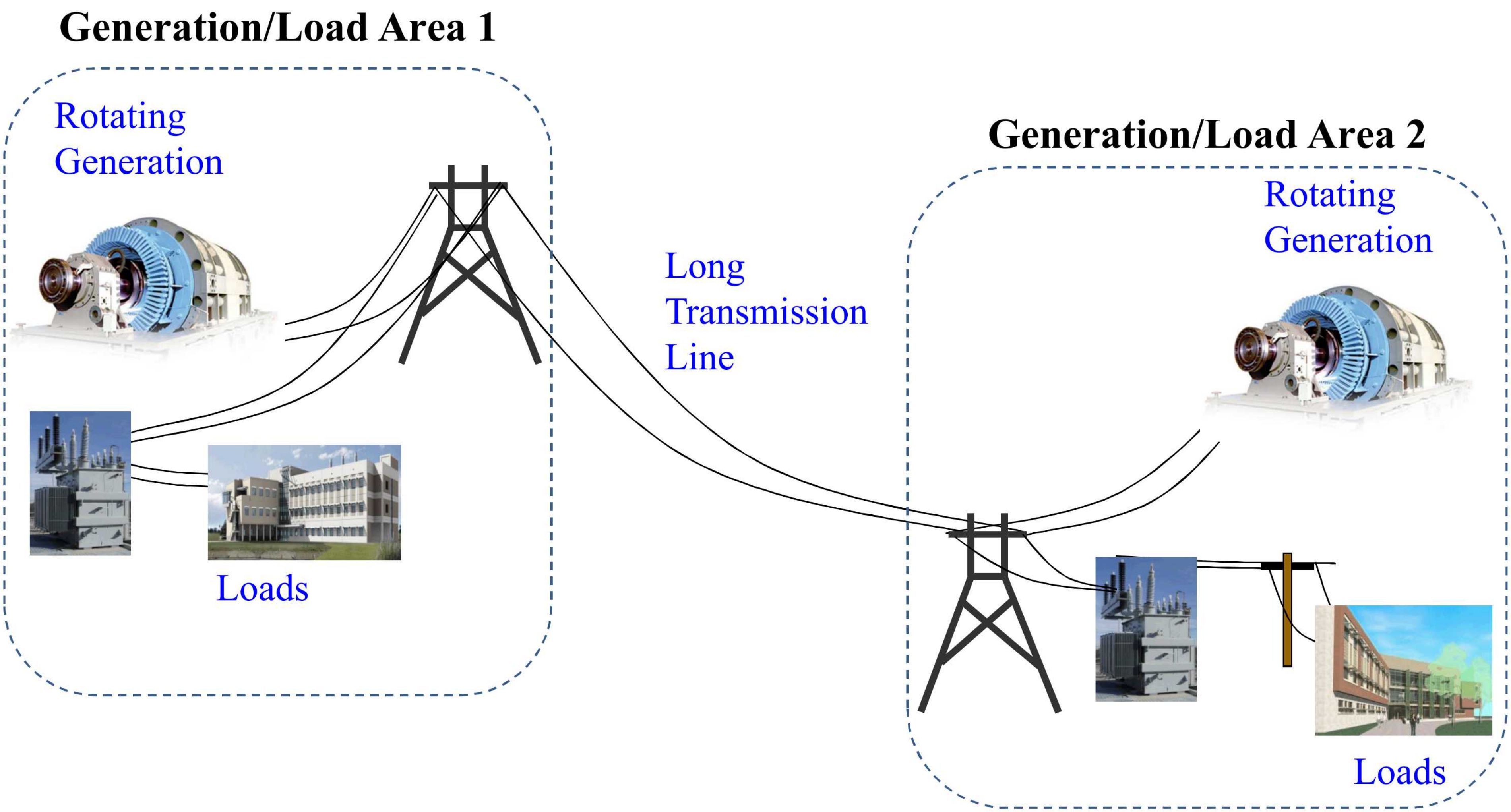


Frequency vs. Power



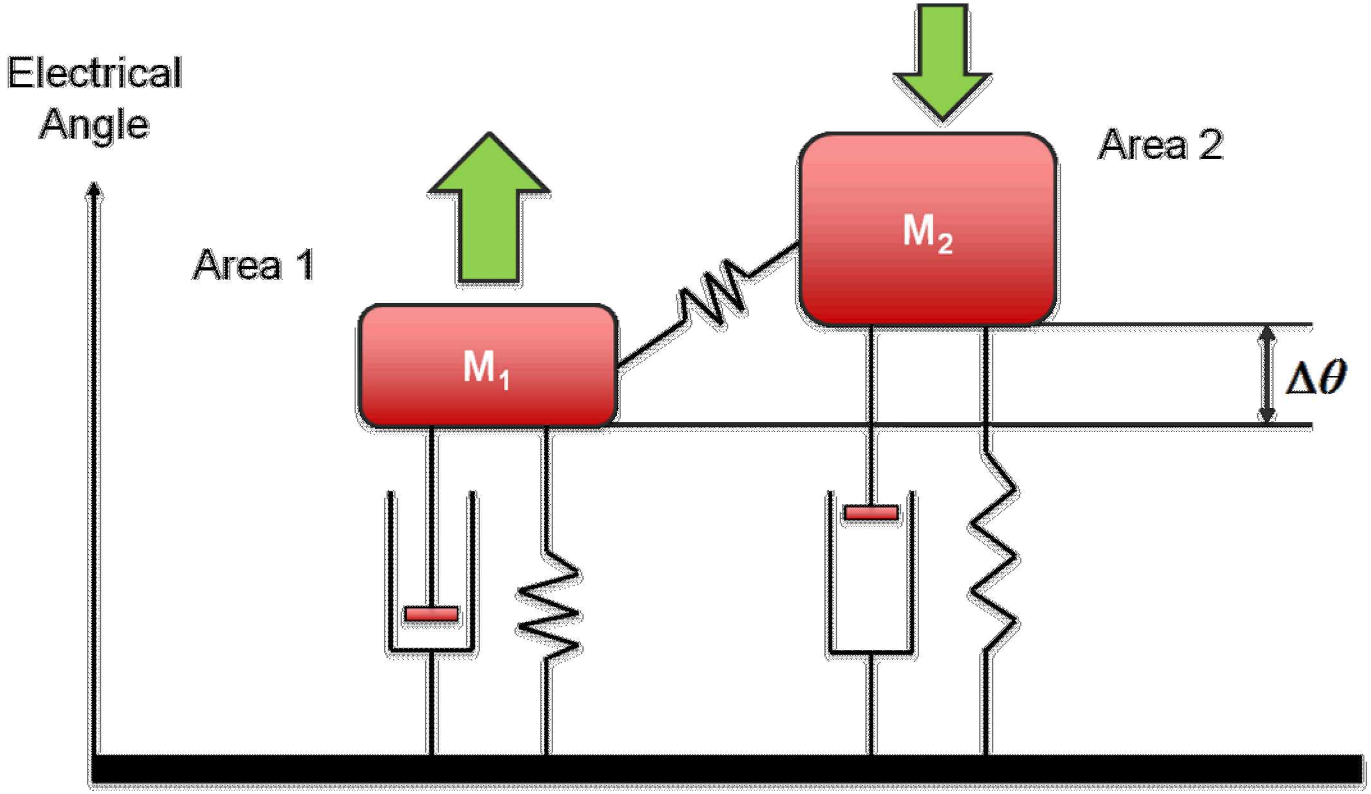
Grid Dynamics and Damping Inter-Area Oscillations

Problems May Arise between Areas Connected by 'Weak' Transmission



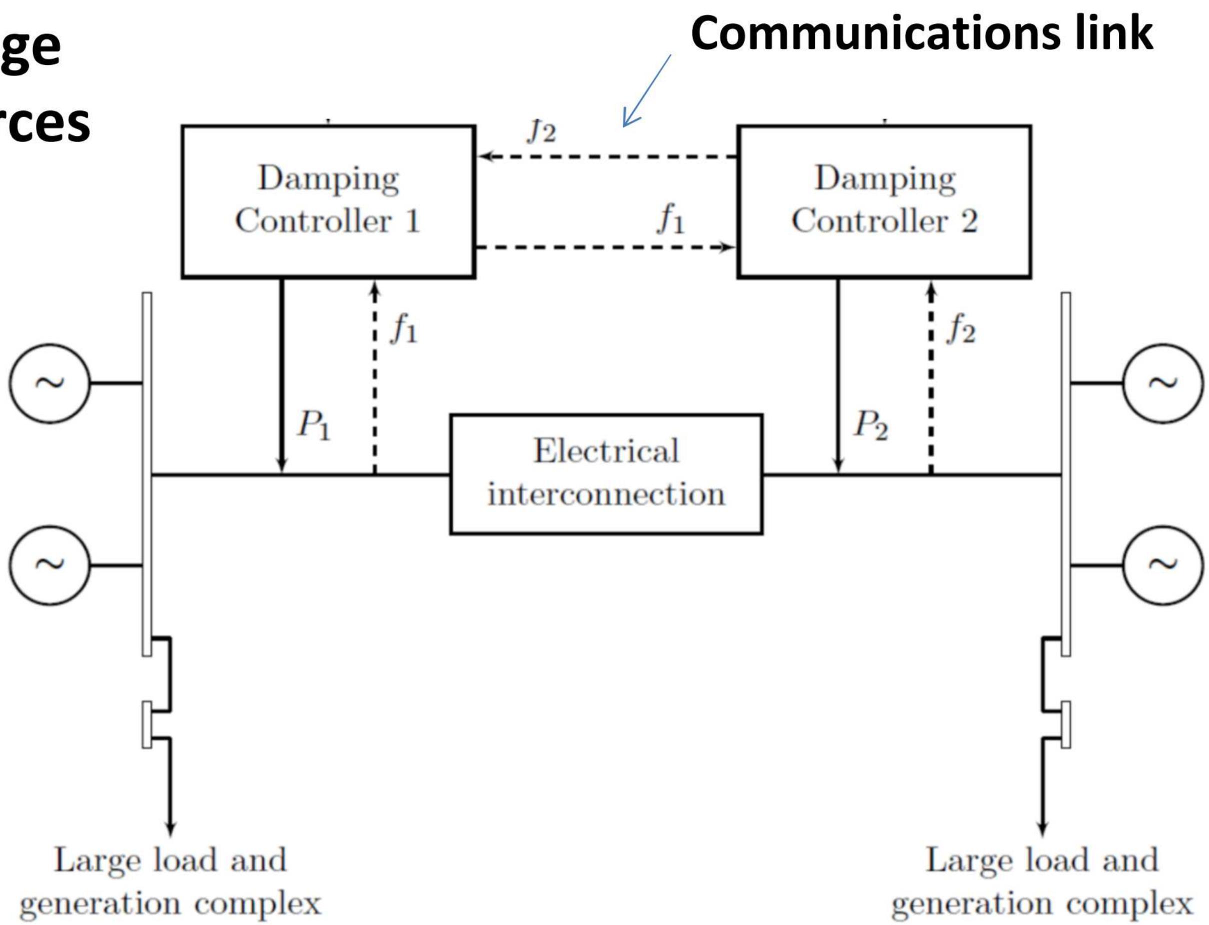
Problems May Arise between Areas Connected by ‘Weak’ Transmission

- **Generator/Load complexes behave like mass-damper systems**
- **The “spring” connecting areas gets weaker with greater power flow resulting in *Inter-Area oscillations***
  - **transmission is usually limited**



Damping Control System can Improve Grid Stability

- **Damping control system delivers power to dampen inter-area oscillations between two or more areas**
  - **High Voltage DC transmission**
  - **Energy Storage**
  - **Other resources**



Visualization of Oscillation Modes

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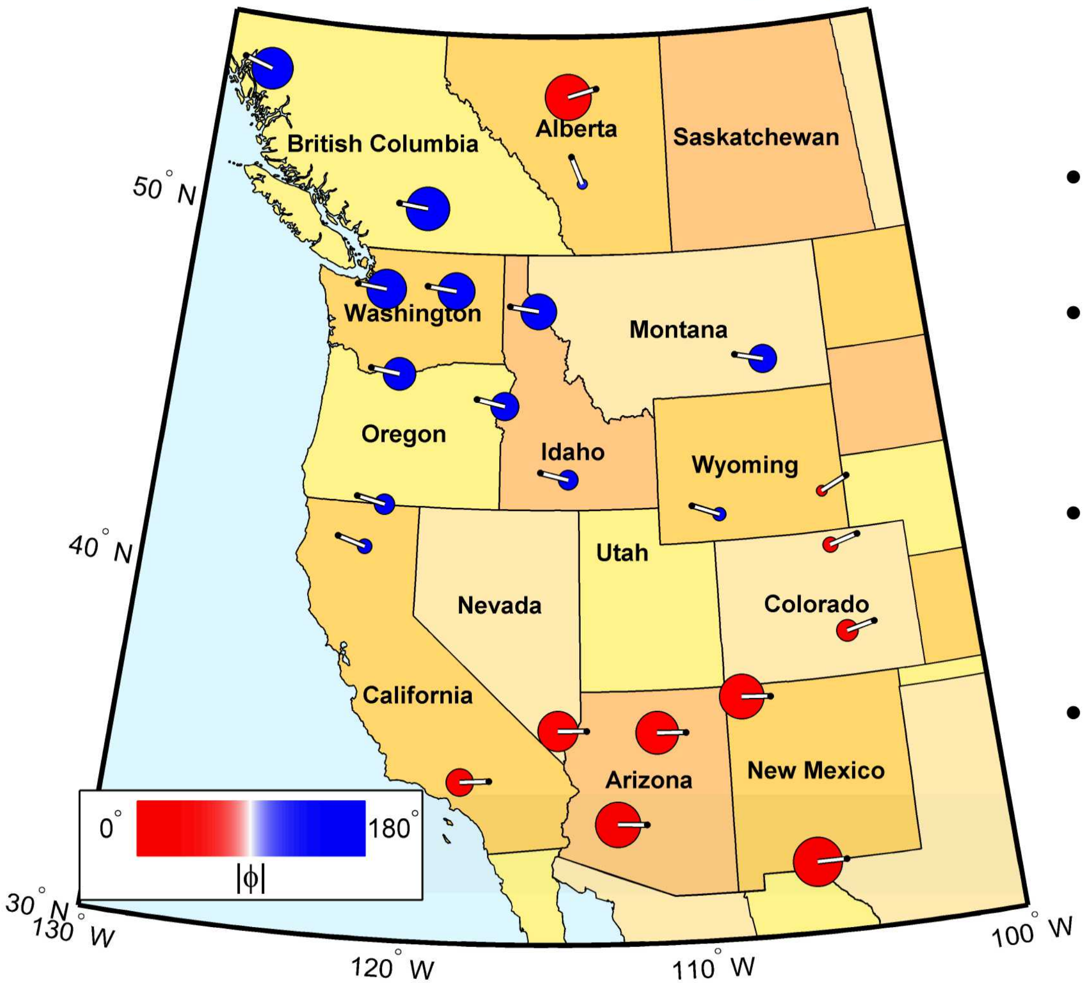
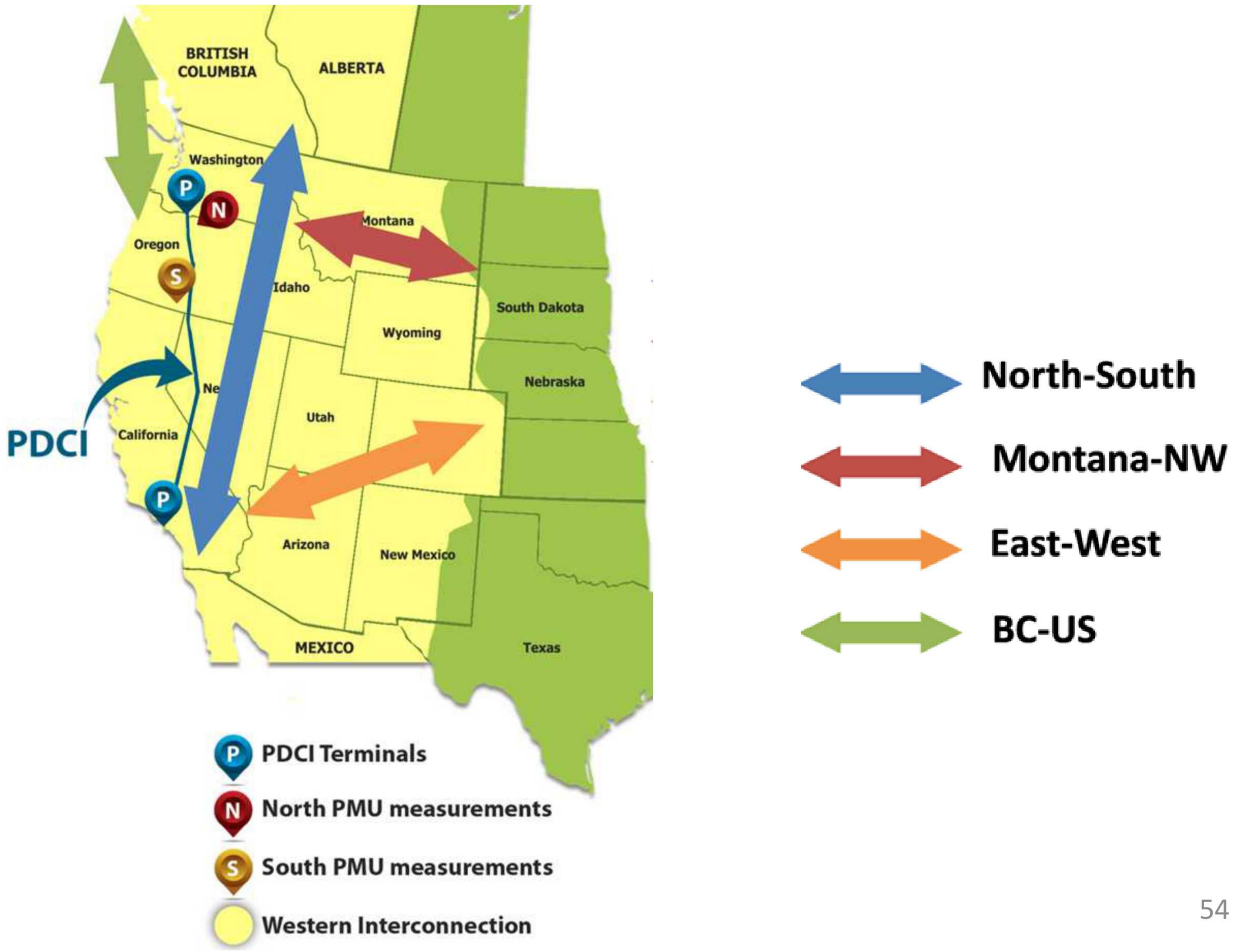
North South Mode
0.36 Hz, 13.7% damping



- Reference site is the location with the largest observed amplitude for that mode.
- Amplitude is proportional to radius of disk
- Color of disk indicates if site was in (red) or out of phase (blue) with reference site.
- Phase angle is indicated by a fixed length arrow in the center of each disk
- Mapping results based upon simulations using 2015 heavy summer base case

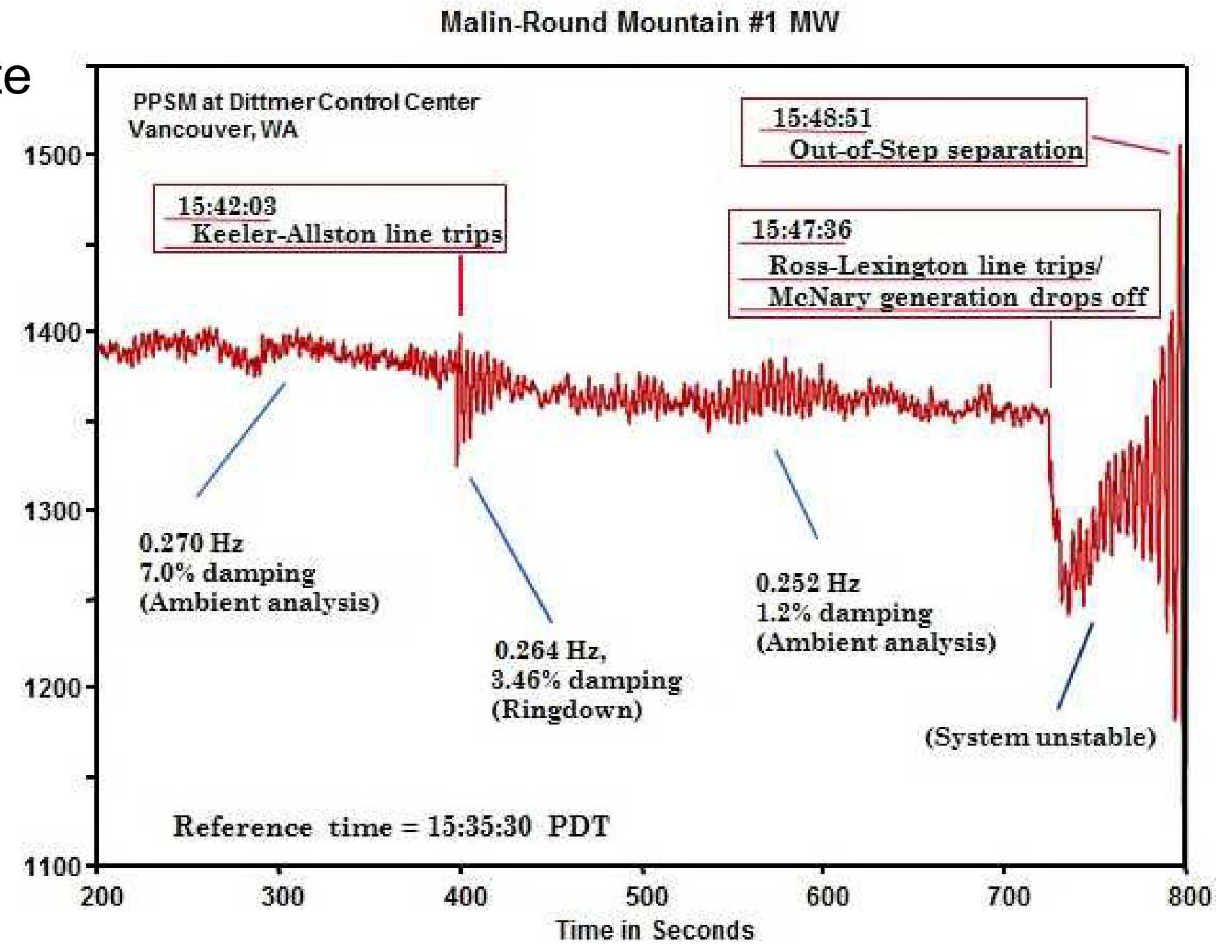
Western Interconnection Oscillation Modes



Inter-Area Oscillations Jeopardize Grid Stability

Western Power System Breakup August 10, 1996

- Present approach to mitigate this scenario is to maintain large headroom in power flow
- More efficient mitigation strategy is active power injection using real-time Phasor Measurement Unit (PMU) feedback



Pacific DC Intertie (PDCI)

- High Voltage DC line: +/- 500 kV
- 3220 MW capacity
- 850 miles long – Celilo to Sylmar
- BPA operates Celilo
- LADWP operates Sylmar
- Operational since 1970
- PDCI is annually used for probing tests (since 2008) to identify and better understand inter-area oscillations on the western grid

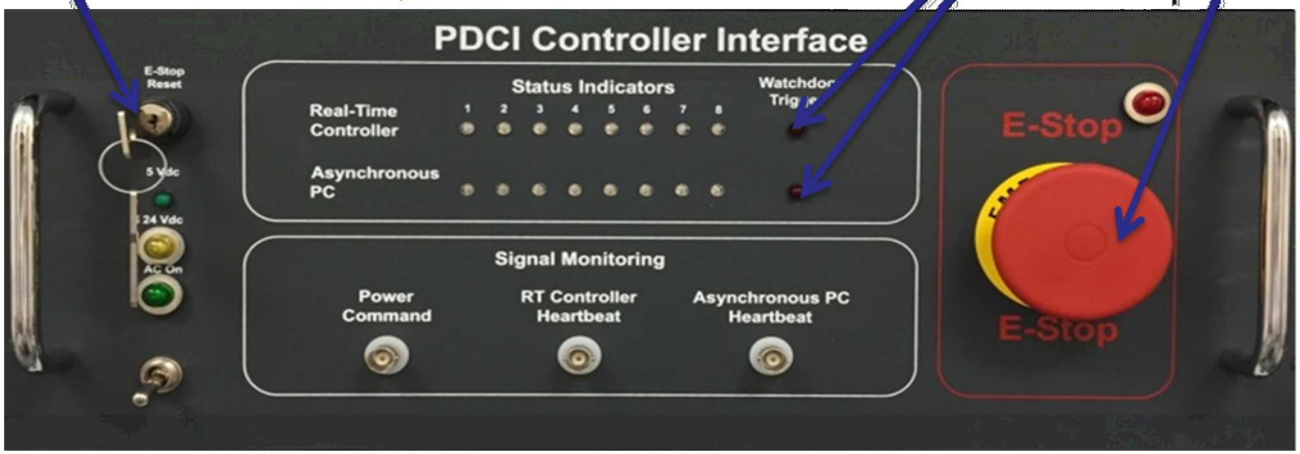
Damping Controller Hardware

Watchdog circuit module

Key switch

Heartbeat indicators

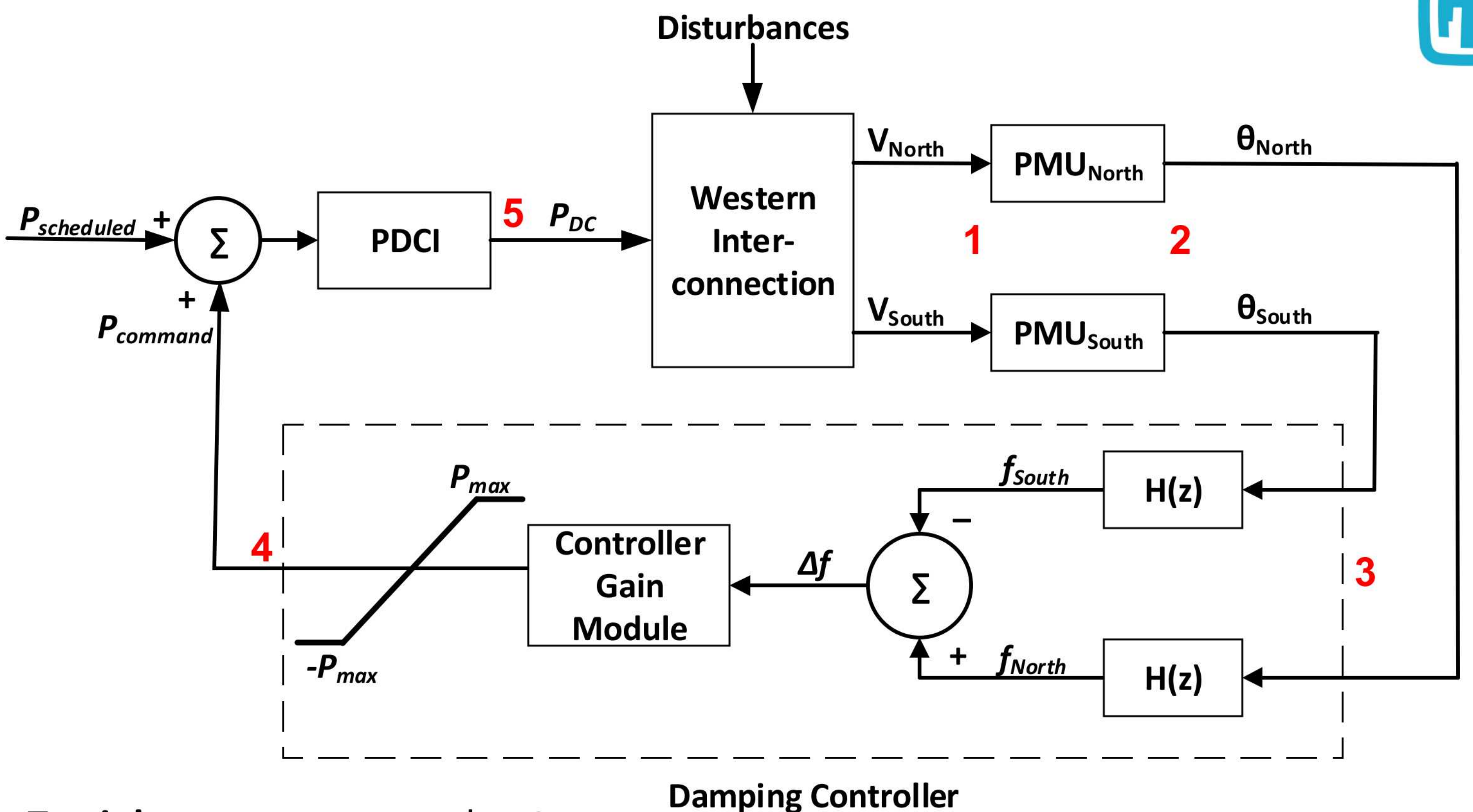
E-Stop button

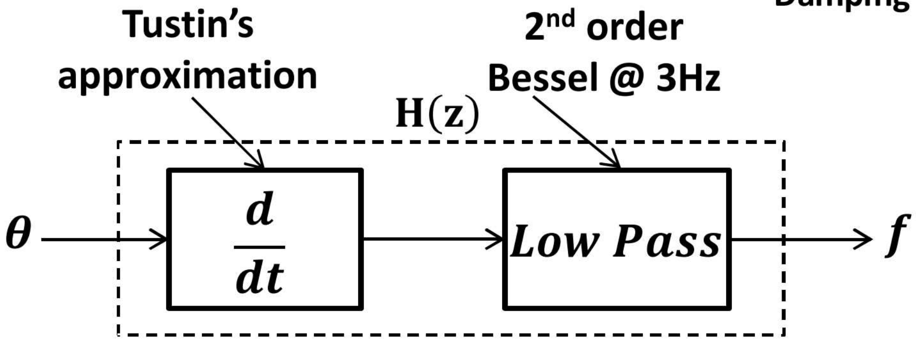


Server for select supervisory functions

Real-time Control platform

Damping Controller Strategy





$$P_{command}(t) = K\left(f_{North}(t-\tau_{d1}) - f_{South}(t-\tau_{d2})\right)$$

K is a constant gain with units of MW/mHz

1 PMUs take measurements

2 PMUs send data packets over network

3 Packets arrive at damping controller

4 Controller sends power command to PDCI

5 PDCI injects power command into grid

Chief Joseph Dynamic Braking Resistor

- Purpose – Transient Stability: Remedial Action Scheme (RAS) to handle large faults in western grid
- Can dissipate 1400 MW for 0.5 – 1.0 sec
- Side Benefit – Ideal as an impulse response to the grid ➔ Aids system identification and control system testing
- History – Built in early 1970s
- Owned & operated by BPA
- Described in M. Shelton et al., “Bonneville Power Administration 1400-MW braking resistor,” IEEE Trans. Power Apparatus & Syst., vol. 94, no. 2, pp. 606-611, 1975.

Grid Demonstrations Showed Significant Improvements in Damping

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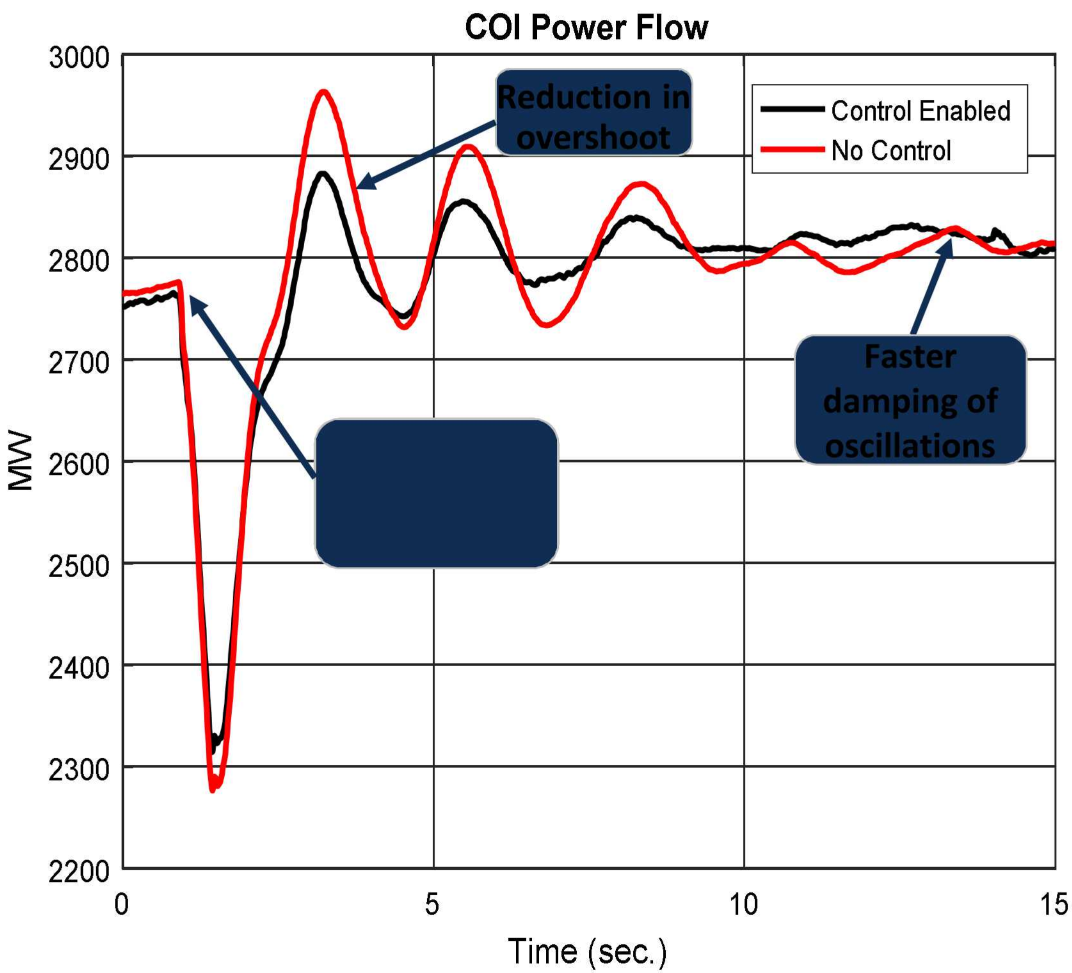
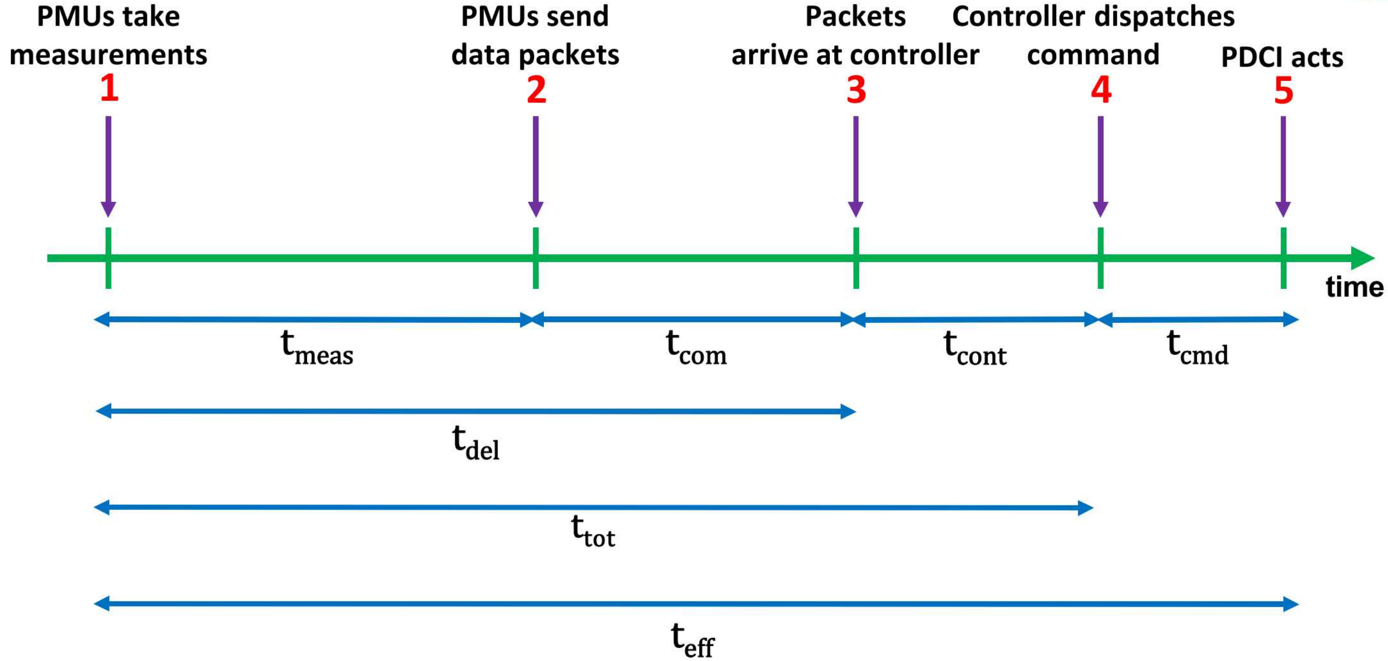
Experiments conducted at Celilo Converter Station Sept 2016, May & June 2017



Chief Joseph brake test	Damping of North-South B Mode improved 4.5 percentage points (11.5% to 16.0%) in closed-loop vs. open-loop operation.
Square wave pulse test	Damping controller significantly reduces amplitude of North-South B mode oscillations in 15 seconds vs. 23 seconds in open-loop tests for the same reduction.
All tests	Controller consistently improves damping and does no harm to grid.

Time Delays in PDCI Damping Control



Symbol	Name	Mean	Range	Distribution
t_{meas}	PMU Delay	50 ms	Assumed fixed at 50 ms	N. A.
t_{com}	Communications Delay	10 ms	[5,38]	Heavy Tail Normal
t_{del}	Signal Delay	60 ms	[55,88]	Heavy Tail Normal
t_{cont}	Control Processing Delay	11 ms	[3,17]	Bimodal Normal with peaks at 8 & 15 ms
t_{tot}	Total Controller Delay	71 ms	[58,102]	Bimodal Normal with peaks at 66 & 73 ms
t_{cmd}	Command Delay	Estimated at 11 ms	Assumed fixed at 11 ms	N. A.
t_{eff}	Effective Delay	82 ms	[69,113]	Bimodal Normal with peaks at 77 & 84 ms

Conclusion: Round trip time delays < 100 ms ➔ well within bounds for robust closed-loop control

The Damping Control Project was a Real Success

Sandia National Laboratories

- First successful demonstration of wide-area control using real-time PMU feedback in North America
- Experience gained in networked controls will advance control design using other network-enabled assets, such as energy storage, smart inverters, and demand response.
- Supervisory system architecture and design can be applied to future real-time grid control systems to ensure “Do No Harm”.
- Extensive eigensystem analysis and visualization tools developed for simulation studies and analysis of test results.
- Model development and validation for multiple levels of fidelity to support analysis, design, and simulation studies.

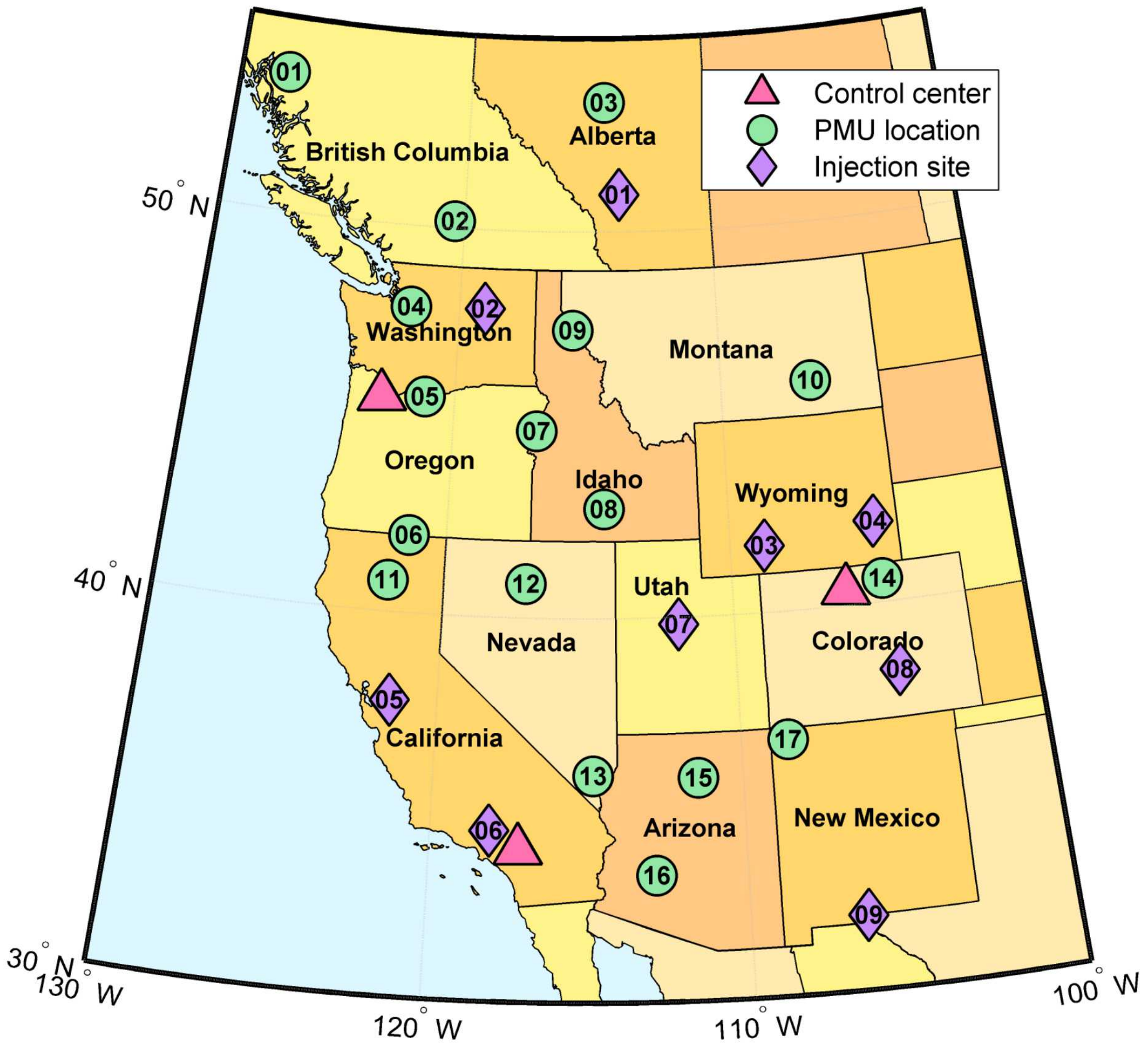
2017 R&D 100 Award Winner

Future Methods will Combine Distributed Sensing with Distributed Modulation

Multi-Node Distributed Control

<u>**Advantages:**</u>

- **Robust to single points of failure**
- **Controllability of multiple modes**
- **Size/location of a single site not as critical as more distributed energy resources are deployed**

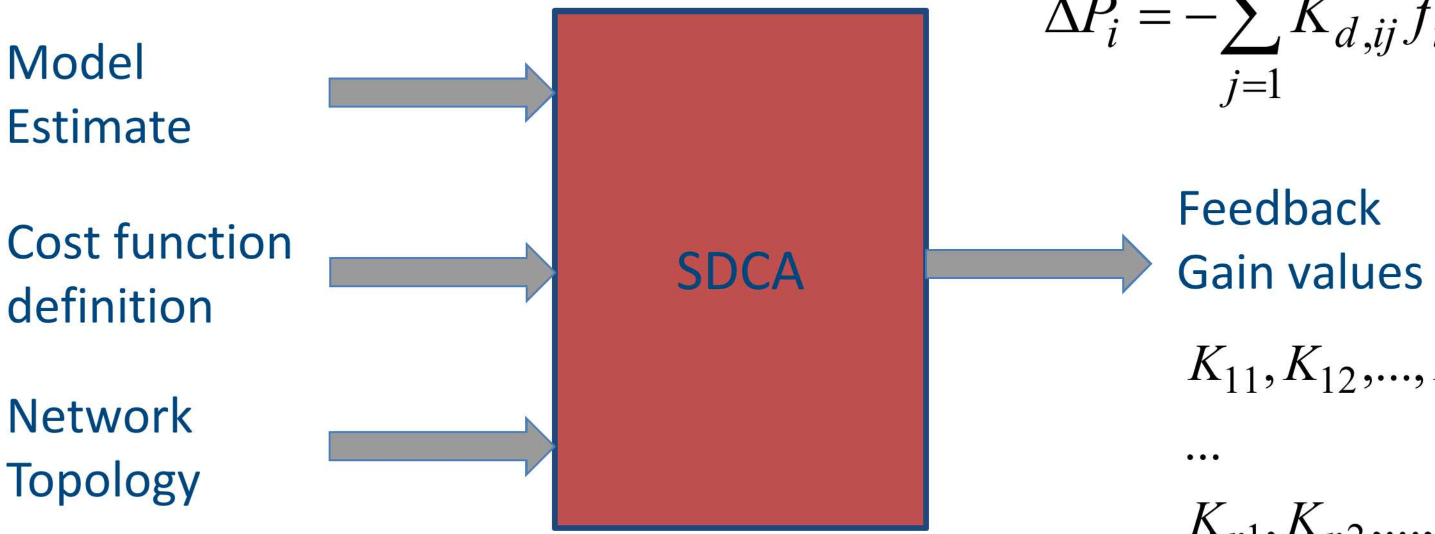


Multi-Node Distributed Damping

Sandia National Laboratories

- Multi-node damping provides redundancy and improved controllability of multiple modes
  - Work is underway to develop a scalable *N*-node damping control scheme based on distributed energy storage with "Tailored Gains"
  - Each node modulates power based on local PMU and multiple remote PMU measurements
- Gains are computed using a Structured Damping Control Algorithm (SDCA)

$$\Delta P_i = -\sum_{j=1}^{n} K_{d,ij} f_i$$



$$K_{11}, K_{12}, \ldots, K_{1n}$$

$$\ldots$$

$$K_{n1}, K_{n2}, \ldots, K_{nn}$$

An Optimization Problem is Formulated

- To attain the control law $u_d = -K_d y$

$$\underset{K_d}{\text{minimize}} \quad J = \int_0^{T_f} \left(x^T Q x + u_d^T R u_d \right) d\tau$$

$$\text{subject to:}$$

$$(1)\ \dot{x}(t) = Ax(t) + B_q q(t) + B_d u_d(t)$$

$$(2)\ y(t) = \begin{bmatrix} \Delta\omega_1 & \Delta\omega_2 & \cdots & \Delta\omega_m \end{bmatrix}^T$$

$$(3)\ u_d(t) = -K_d y(t)$$

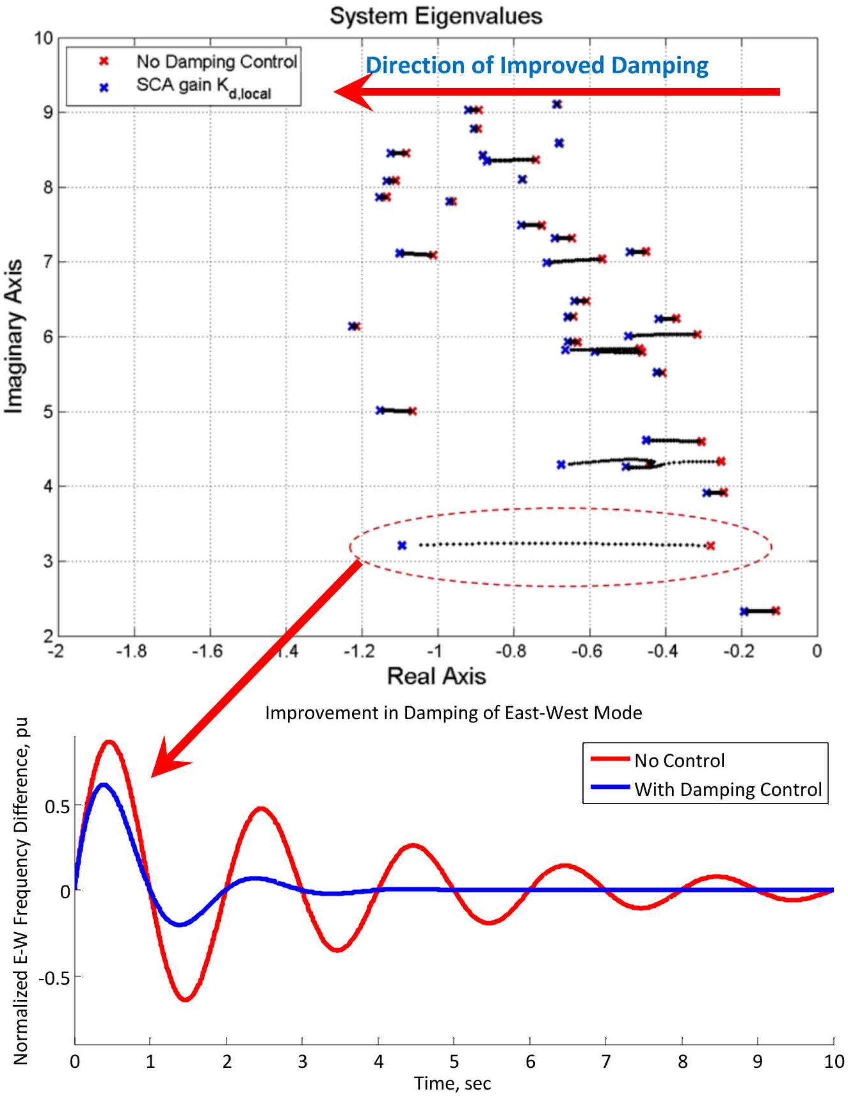
$$(4)\ Q \geq 0, R > 0$$

- The above optimization problem must be solved iteratively
- For solution details, see the recent journal paper:

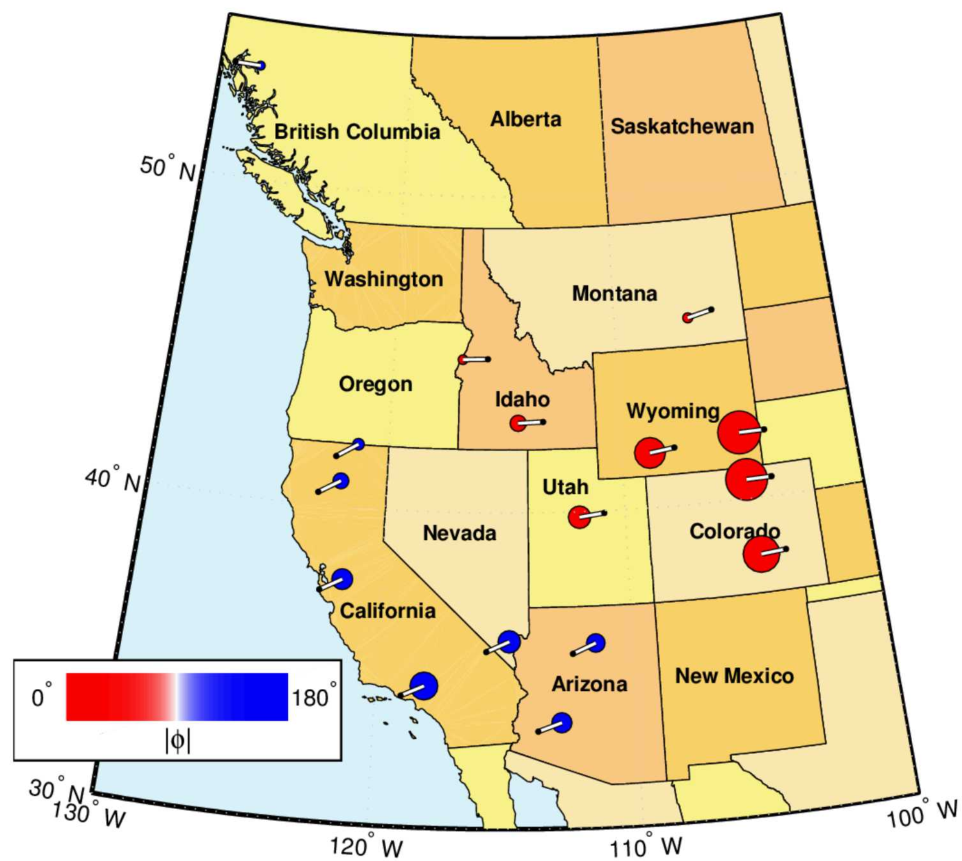
J. Neely, J. Johnson, R. Byrne, and R. Elliott, "Structured Optimization for Parameter Selection of Frequency-Watt Grid Support Functions for Wide-Area Damping," *International Journal of Distributed Energy Resources and Smart Grids*, vol. 11, no. 1, pp. 69-94, 2015.

Example using Distributed Energy Storage

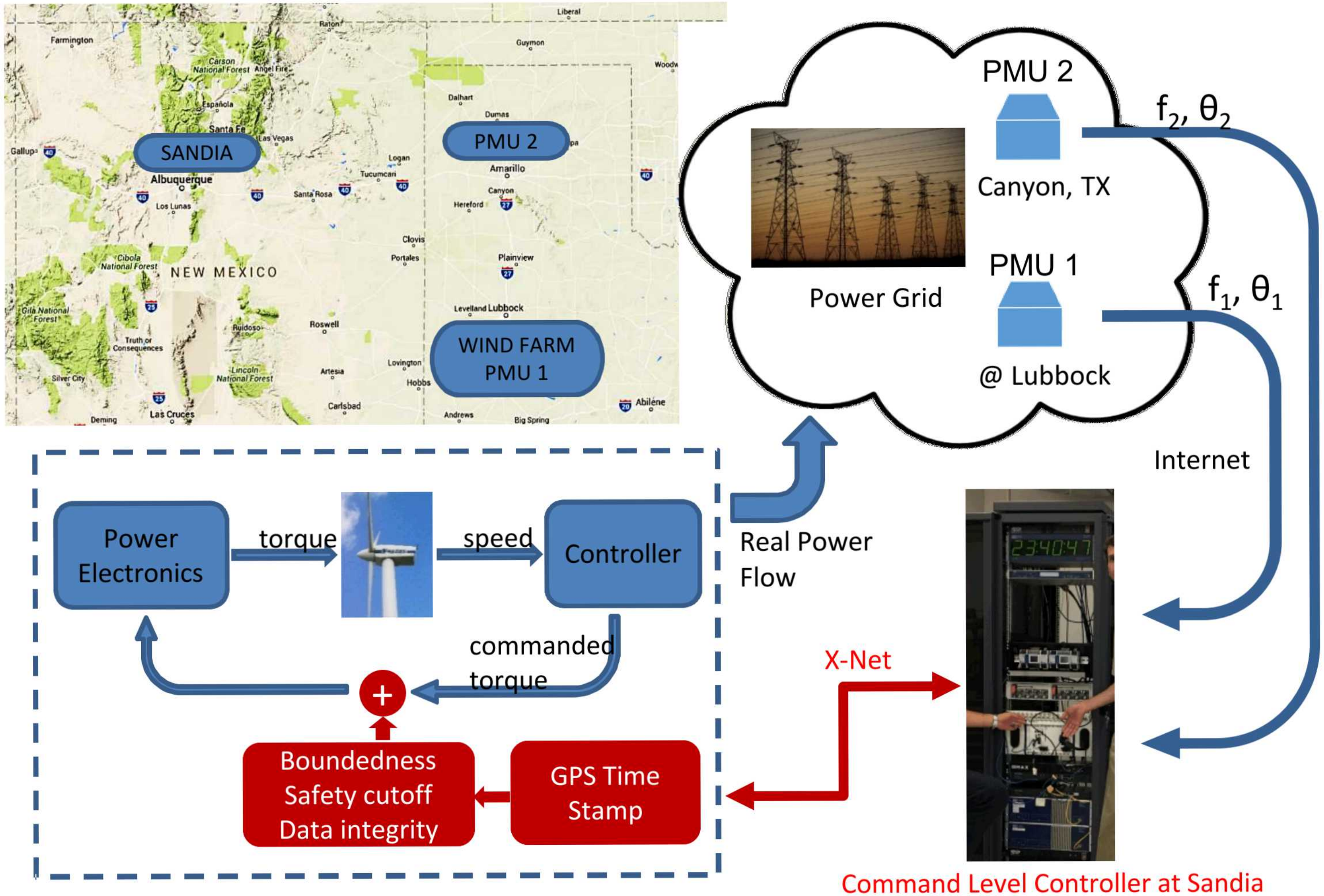
- Total real power capacity on order of 20 – 50 MW is sufficient
- With 10s of sites deployed, individual resource capacity ≤ 1 MW will work



East-West Mode



Network-Based Modulation of Power in Wind Turbines



- Modulation of wind power implemented in turbine nacelle at wind farm in Lubbock, TX.
- Command level controller implemented at Sandia in Albuquerque, NM.
- Successful demonstration of coordinated control strategy on Sept. 28, 2017.
- Outcome is scalable, giving wind operators the opportunity to provide valuable grid services.

Some Concluding Remarks …

Sandia National Laboratories

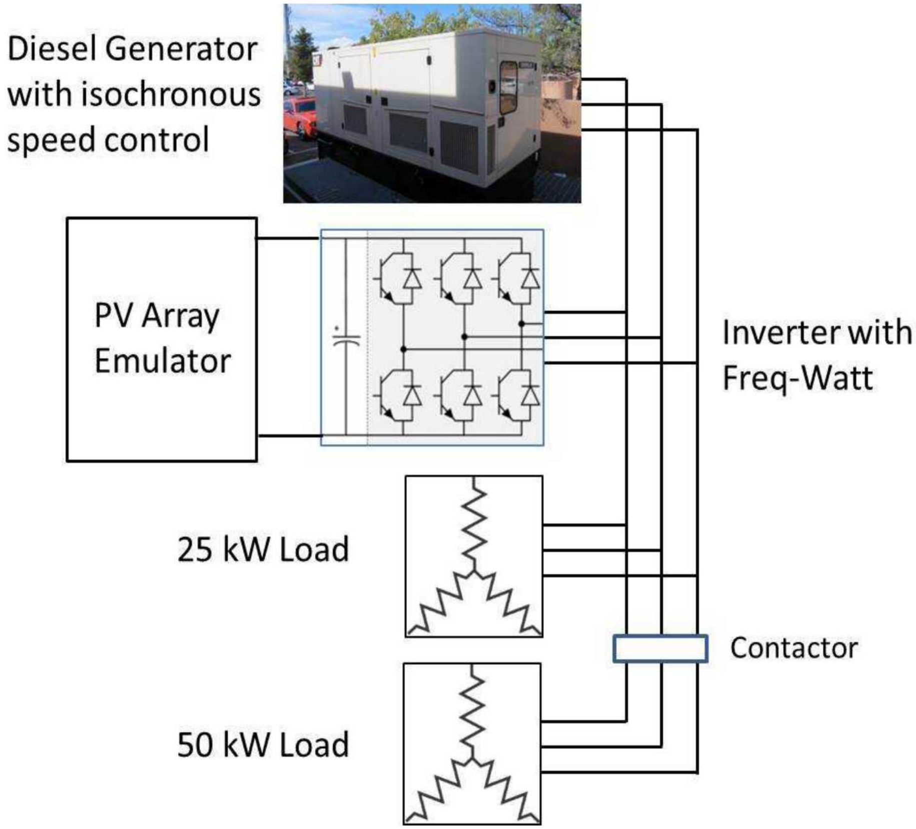
- Over the last 100+ years, the grid has become reliant on large centralized fossil-fuel based power generation
- As large centralized power generation is displaced by distributed energy sources, new controls approaches are needed to maintain grid operation
- The “SMART Grid”, enabled by new controls, holds great promise for realizing the *Grid of the Future*

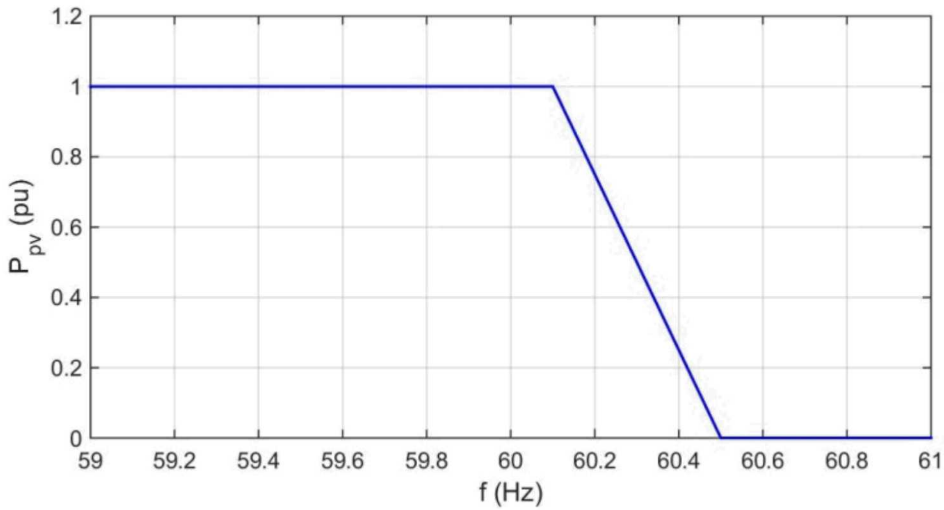
Backup slides

Frequency Watt was Tested in a Lab-Sized 'Island Grid'

– A hardware testbed was assembled

- 225 kW diesel generator
- 24kW inverter with FW capability
- Resistive load switching between 25kW and 75kW

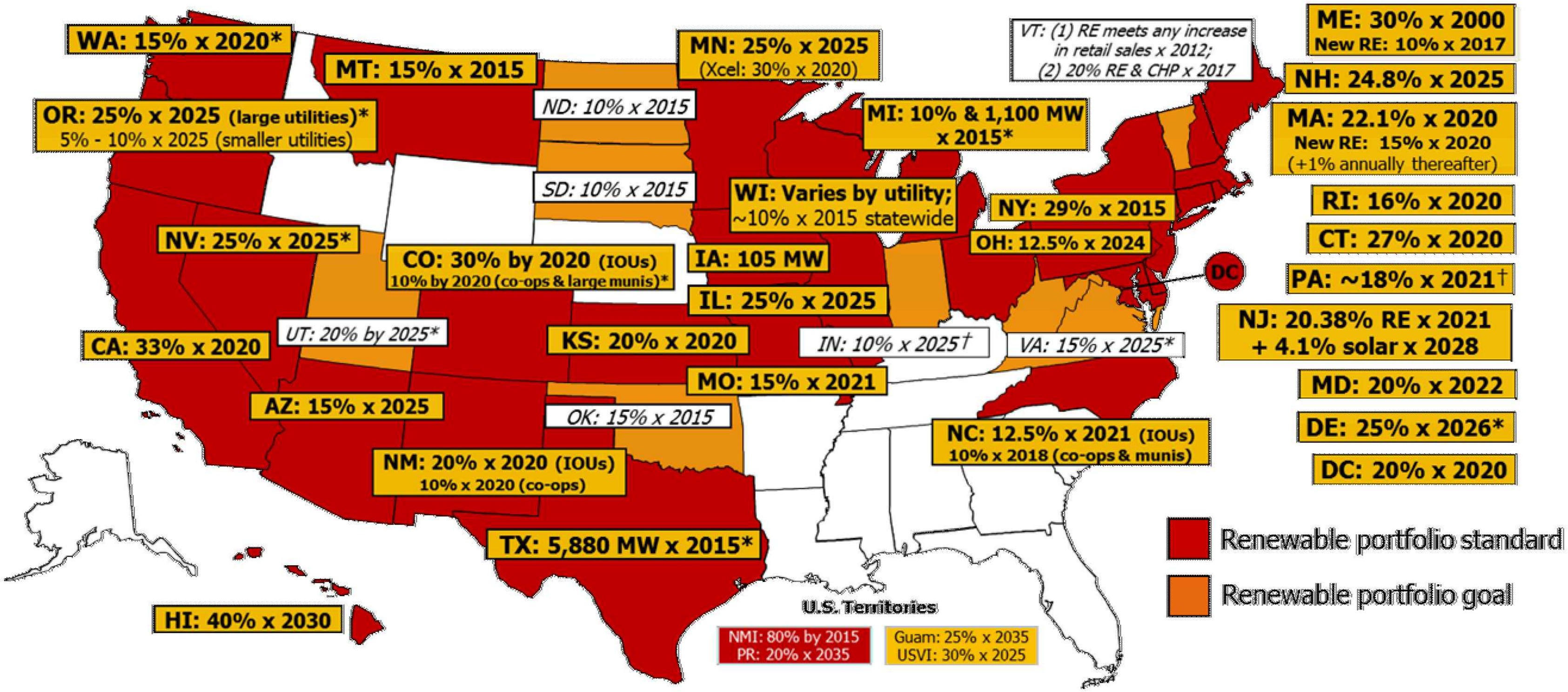




States are Committing to Renewable Energy Integration

Sandia National Laboratories

- **29 state governments, Washington DC, 2 territories have committed to new *Renewable Portfolio Standards***



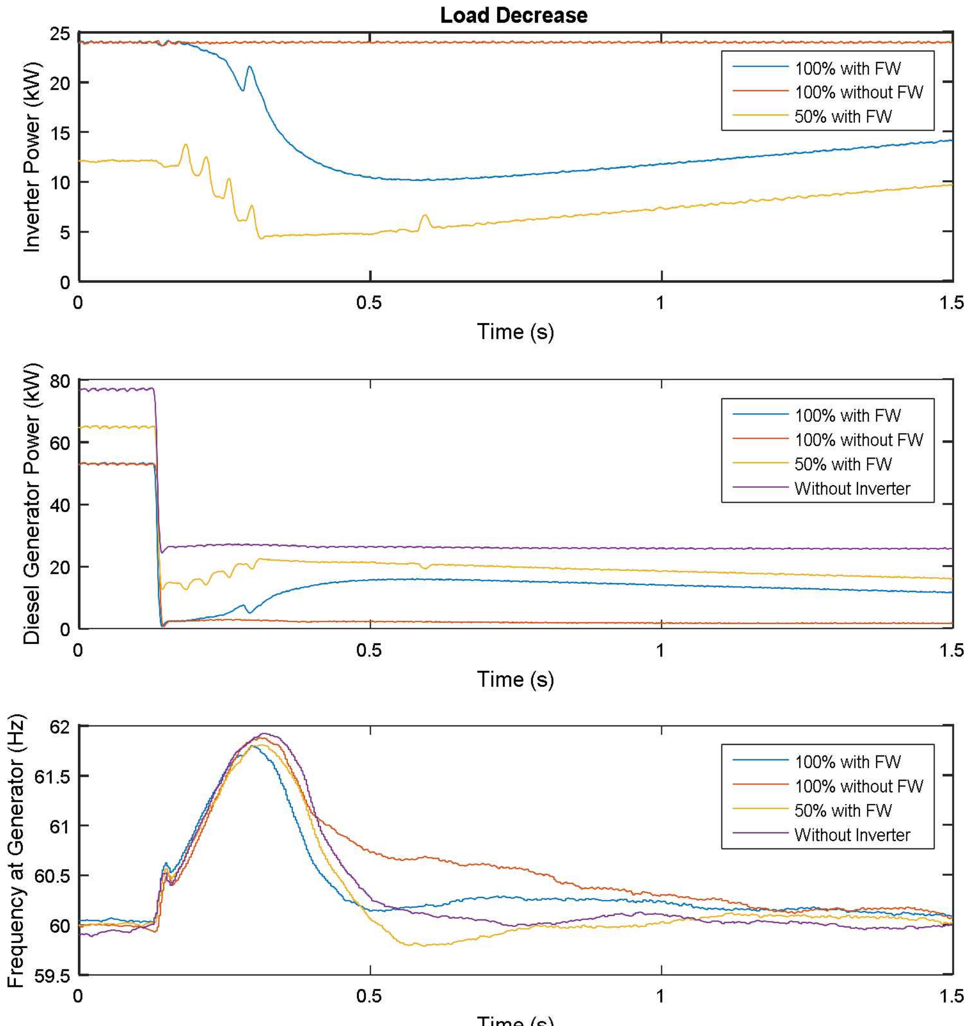
DSIRE database, November 2013

Database of state incentives for renewables and efficiency renewable portfolio standards
http://www.dsireusa.org/

Frequency Watt was Tested in a Lab-Sized 'Island Grid'

– Load Step Change from 75kW to 25kW

- Use of the FW function reduces peak frequency and improves the rate at which frequency returns to nominal



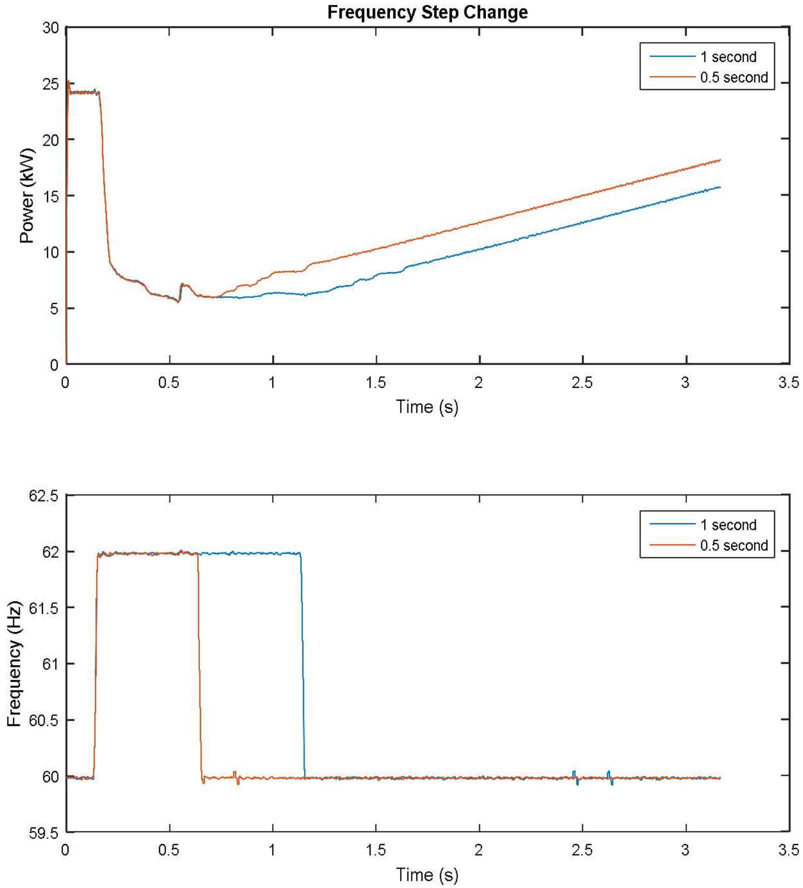
Scenario	Integral Squared Frequency Error f_e (Hz)
Inverter at 100% capacity with FW enabled	0.50993
Inverter at 100% capacity with FW disabled	0.75181
Inverter at 50% capacity with FW enabled	0.51738
Diesel generator with no inverter	0.61614

$$f_e = \int_{t_0}^{t_s} (f(\tau) - f^*)^2 d\tau$$

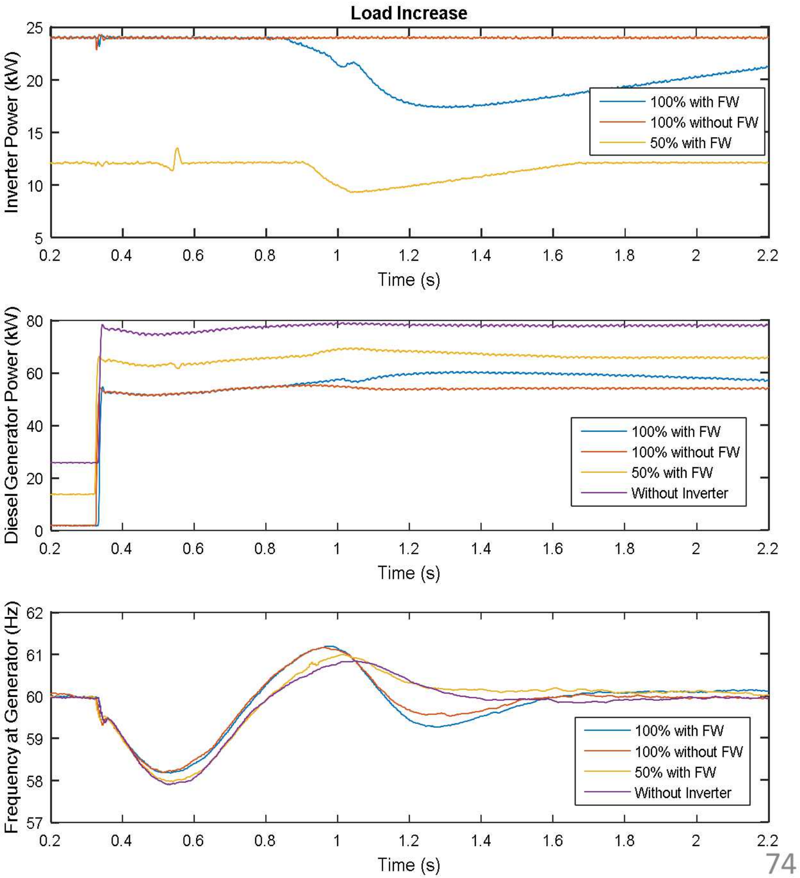
Frequency Watt was Tested in a Lab-Sized 'Island Grid'

– Built-in inverter time delay can limit FW effectiveness

Response to change in grid frequency

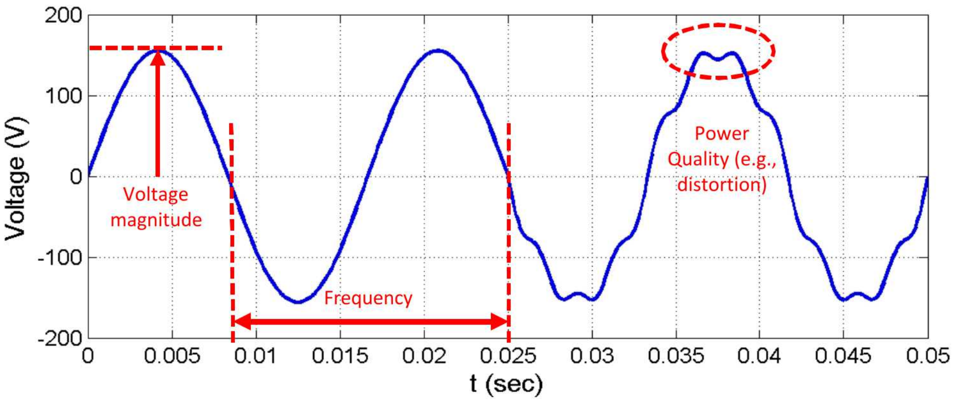


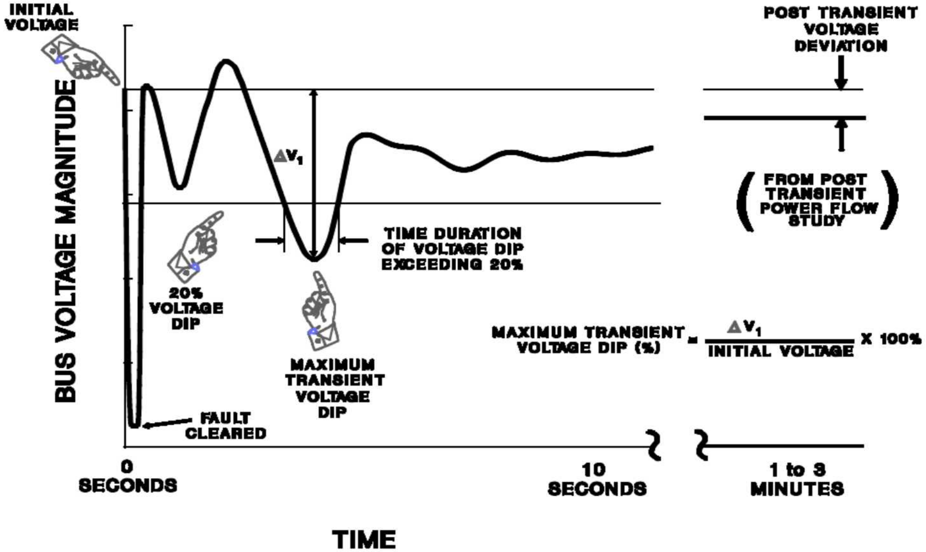
Load change from 25kW to 75kW



Grid performance requirements

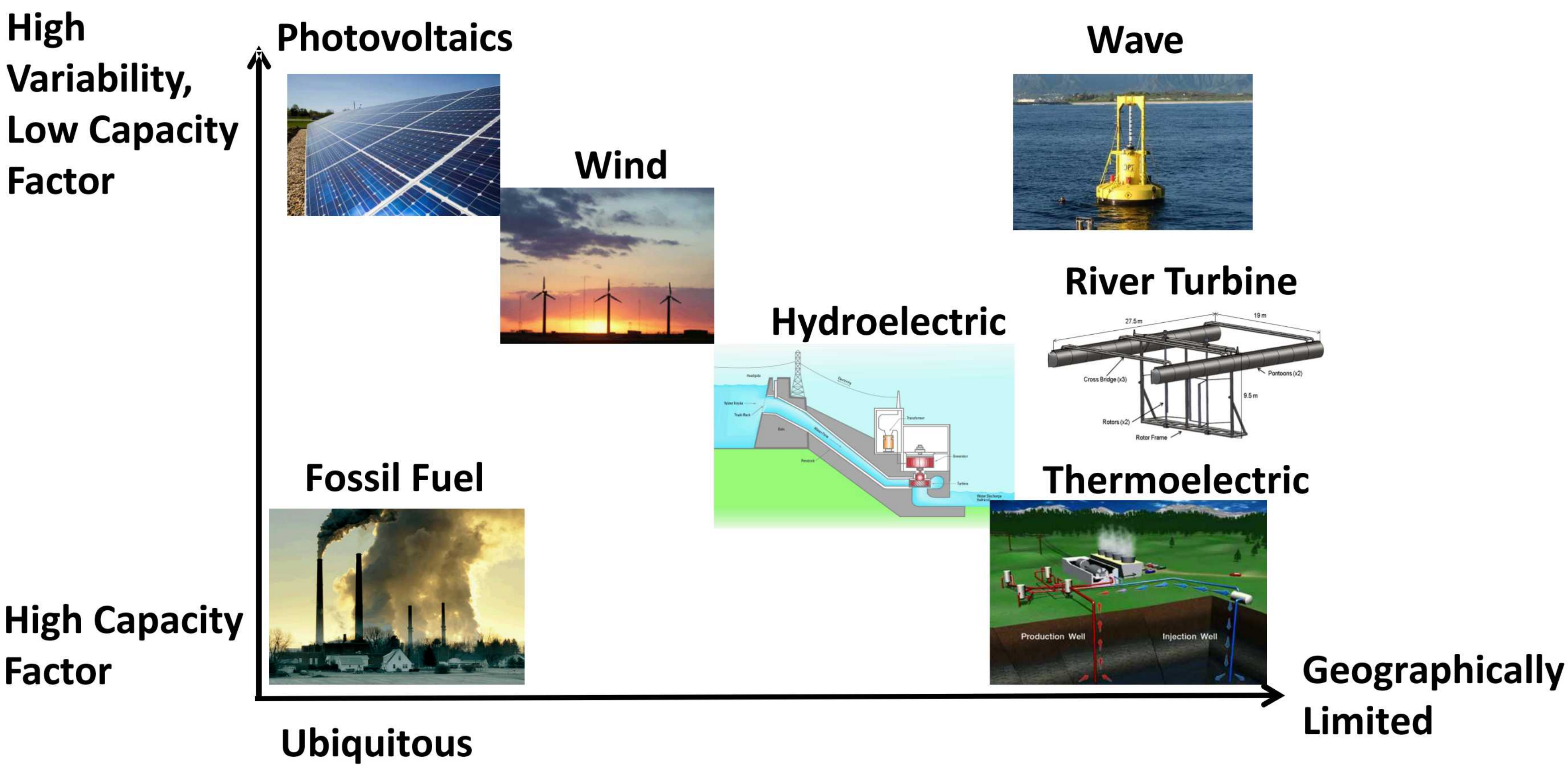
- **Voltage & frequency control**
- **Protection**
  - How to tell when/where there is a problem (e.g., fault)
  - Ensure safety, prevent damage to equipment, avoid cascading
- **System stability**
  - How voltage and frequency recover from a disturbance
- **Continuity of service**
  - Benchmark: 1-day cumulative outage per customer in a 10-year span (99.97% reliable)





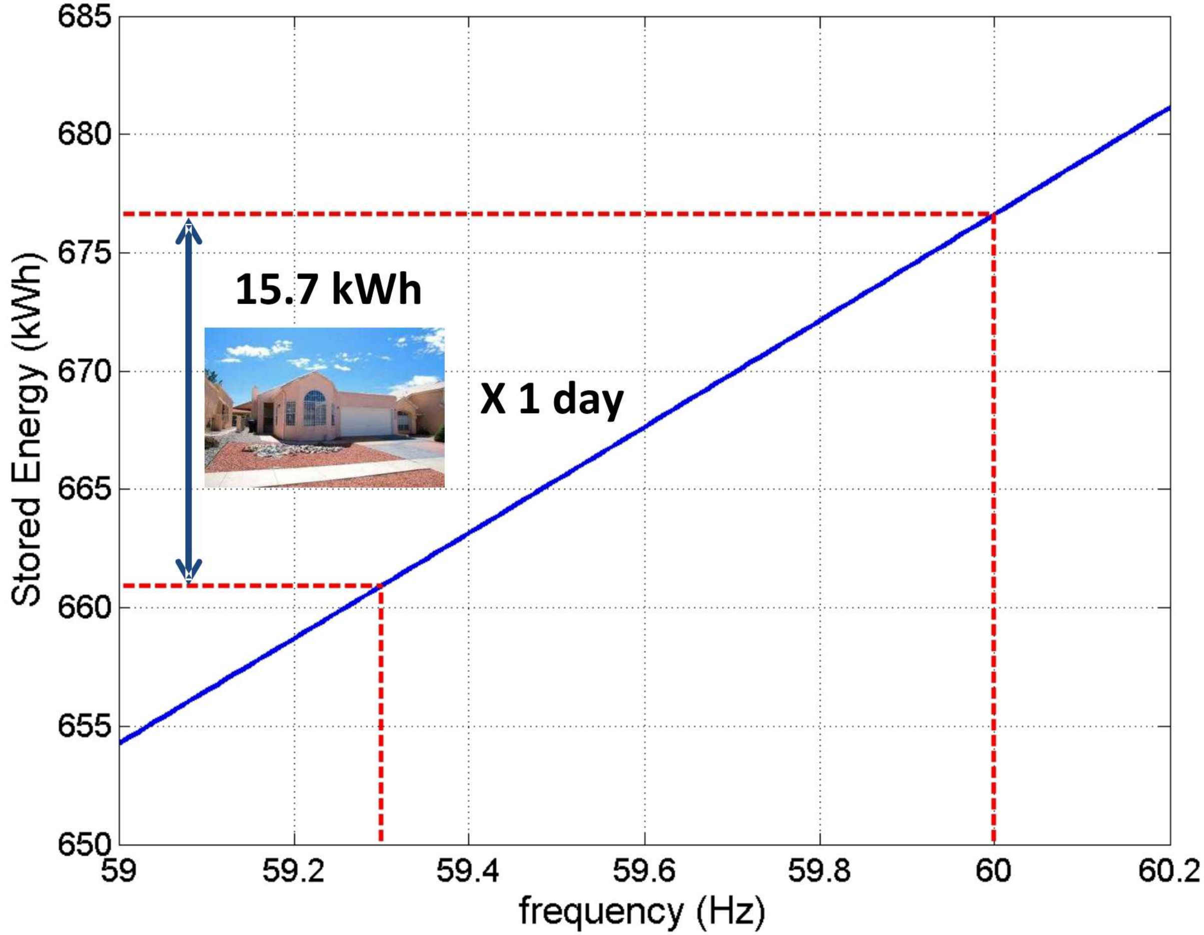
What are Some of the Tradeoffs?

- **Grid-tied renewable energy tends to have limited geographic availability or high variability**



‘Inertia’ Plays a Key Role in Grid Dynamics

Example: 325 MVA Hydro Turbine Generator[1]



[1] P. Krause, O. Wasynczuk, S. Sudhoff; Analysis of Electric Machinery and Drive Systems; 2nd ed